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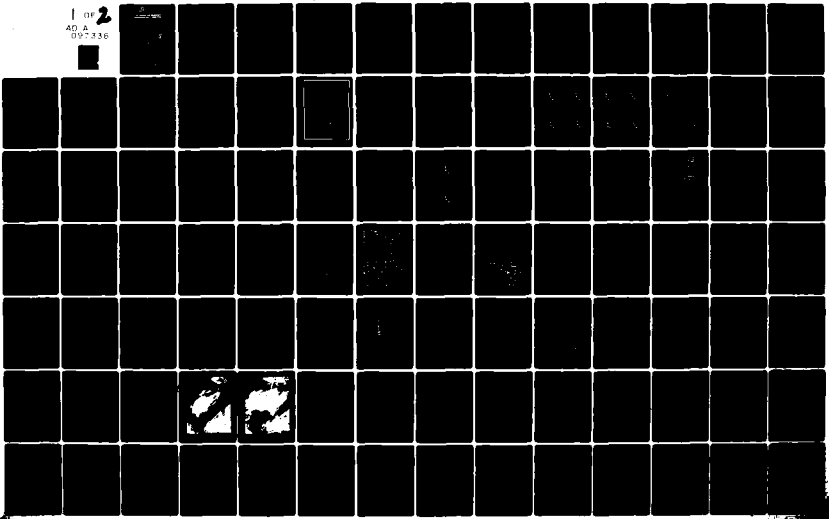

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CALSPAN ADVANCED TECHNOLOGY CENTER

AN INVESTIGATION OF MARINE FOG FORECAST CONCEPTS

by

C.W. Rogers, E.J. Mack,
R.J. Pilie,[redacted] B.J. Wattle

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Eighth Annual Summary Report

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) As a follow-on to eight years of field study of marine fog, an investigation of potential fog forecasting concepts was initiated. Task 1 involved examination and interpretation of synoptic scale meteorological data in terms of micro- and meso-scale marine fog data acquired by Calspan on previous West Coast field studies. The results of this investigation were summarized in an experimental "decision tree" for use in the forecasting of marine fog. As Task 2, Calspan conducted a descriptive investigation of the circumstances and characteristics of marine fog occurring in the northern Gulf of Mexico through analysis and interpretation of fog data previously acquired by Calspan during the Panama City II experiment.

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Section 1
INTRODUCTION

For the past eight years under sponsorship of the Naval Air Systems Command (NASC), Calspan Corporation in cooperation with the Naval Postgraduate School (NPS), the Naval Research Laboratory (NRL), and the Naval Avionics Center (NAC) has been conducting an investigation of the evolutionary processes and physical properties of marine fog and marine boundary-layer aerosols. During the first four years, attention was focused on determination of the formation mechanisms and physical and chemical characteristics of marine fogs occurring off the coasts of California and Nova Scotia. For the past three years, the scope of Calspan's effort was expanded to include investigation of evolutionary processes which control compositional and physical characteristics of marine boundary layer aerosols. Results of these efforts are summarized in References 1-16.

This year, under Contract No. N00019-80-C-0248 from NASC, Calspan continued its contribution to the Navy's Marine Fog Investigation with a program involving two separate tasks and renewed emphasis on marine fog. Task 1 involved investigation of potential fog forecasting concepts by examining and interpreting, in terms of larger scale meteorological processes, micro- and meso-scale marine fog data acquired by Calspan on previous West Coast field studies. As Task 2, Calspan conducted a descriptive investigation of the characteristics of marine fog occurring in the northern Gulf of Mexico through analysis and interpretation of fog data previously acquired by Calspan during the Panama City II experiment.

The objective of the Task 1 effort was to review, analyze and otherwise interpret synoptic scale data for West Coast fog episodes in which Calspan previously acquired micro- and mesoscale information (see Appendix A). Earlier analyses of these micro- and mesoscale data resulted in descriptive, phenomenological models of a number of previously unidentified marine fog types and the elucidation of the importance of such factors as mesoscale convergence patterns, warm water patches, the height and strength of the marine inversion and radiation in the development of marine fog. Under Task 1, we attempted to link this new knowledge of mesoscale fog characteristics to synoptic scale variables available to the operational forecaster. Detailed discussion of the results of this effort is provided in Section 3 and summarized in Section 2. An experimental "decision tree" for use in the forecasting of marine fog is also provided in Section 2.

Under a previous NASC contract (No. N00019-79-C-0186), Calspan in collaboration with NAC, the Naval Coastal Systems Center (NCSC) and the Coastal Studies Institute participated in a study aboard NCSC's offshore platform, Stage I, located ∿20 km southwest of Panama City, Florida. The field effort, dubbed Panama City II, was conducted during a four-week period in November-December 1978 to obtain data describing marine fog and marine boundary layer characteristics in the northern Gulf of Mexico. Aerosol and meteorological data obtained during the Panama City II experiment were reduced and provided in a "data volume" (Ref. 13) under Contract N00163-79-C-0049 from NAC. Aerosol data were partially analyzed under ONR Contract No. N00014-79-C-0033 and summarized in a formal paper (Ref. 16) and a contractor report (Ref. 17). However, fog data could not be analyzed within the scope of the previous contracts. As Task 2 under the current contract, data from the fog episodes of the Panama City II experiment were analyzed and interpreted to provide descriptions of fog characteristics and of the circumstances of fog occurrence in coastal Gulf waters. Results of these analyses are presented in Section 4.

Section 2
SUMMARY OF THE METEOROLOGY OF MARINE FOG OCCURRENCE ALONG THE CALIFORNIA COAST

Fog along the California coast occurs in the surface marine layer, and, given a variety of trigger mechanisms, its occurrence is primarily dependent on the height, fluctuations and strength of the inversion which caps the marine layer. Study of synoptic sequences and associated fog episodes has shown that fluctuations in the height of the marine inversion over periods of days are generally caused by evolution and movement of both large and small scale synoptic disturbances. It is the vertical motion in these disturbances which controls the height of the inversion. Superimposed on these vertical motions are downslope motions along the coast and the influences of convergence-induced vertical motions such as have been documented in the vicinity of prominent points along the coast and over warm water patches.

Climatologically, the summer surface pattern along the California coast shows a northwesterly flow produced between the subtropical high over the ocean and the thermal low over the land. Frequently, within the northwesterly flow, a stratus deck exists which is topped by an inversion separating the cool marine layer from the warmer air aloft. When the inversion base lowers to below 400 m, fog forms at night by a lowering of the stratus base as net long wave radiation from the cloud deck cools the marine layer. When the inversion rises above 400 m, fog is unlikely because the radiative heat loss cannot supply sufficient cooling for the thicker layer. At times, the inversion may be below the lifting condensation level, preventing formation of stratus lowering fog, but allowing radiation fog in coastal areas and radiative cooling of low-level fog patches triggered over sea surface temperature gradients.

While we have not studied the phenomenon quantitatively, there is evidence to suggest that the strength of the marine inversion also plays a role in the occurrence of marine fog. Radiosonde data indicate that transport of heat and moisture across the inversion occurs to a greater extent with less intense inversions and strong heating from below. Our case studies suggest that, on some occasions, this phenomenon prevented the formation of stratus-lowering fog by reducing the net effect of radiational cooling on the marine layer; i.e., warm, dry air was mixed downward into the marine layer.

While fog occurs in the surface marine layer, the inversion's vertical movements which govern fog occurrence are controlled by flow patterns in the layer up to 1500 m. These flow patterns are manifestations of (1) slowly-moving long-wave systems, (2) large-scale synoptic systems whose driving forces operate at mid-atmospheric levels, and (3) small-scale synoptic systems concentrated in the 500-1500 m layer.

When a long wave trough is located near the coast, southwesterly flow and upward vertical motion occur ahead of the trough. The upward vertical motion, both in the marine layer and the warm air aloft, raise the inversion to heights of 1000 m and greater. After the trough moves out and the subtropical high with its northwesterly flow becomes reestablished, the inversion lowers in the downward motion accompanying the high pressure cell. This relationship can be recognized in the early statistical work of Petterssen (1938) which showed that with southwest winds the inversion was above 400 m and with northwest winds the inversion was below 400 m.

In addition to the slowly changing long wave flow pattern, both large-scale and small-scale synoptic disturbances frequently raise and lower the inversion height and, through these movements, control fog occurrence. As an example of large-scale synoptic disturbances, the subtropical high frequently builds onto the continent and produces northeasterly flow in the 500-1500 m layer. With the mountain ranges along the west coast oriented approximately north to south, this flow produces downslope motion which drives both the warm air and the inversion downward to very low levels. Occasionally, the inversion and warm air come to the surface as far westward as the coastline but not far out to sea; this more frequently occurring summer condition is in contrast to the Santa Ana conditions in Fall through Spring when the warm air may move out over the ocean. Although during the summertime the marine layer is still present at sea, an area extending some distance out from the coast is stratus-free as the inversion is forced below the lifting condensation level (LCL) of the marine layer.

The response of the surface pressure pattern to the ridging aloft is a weakening but not a disappearance of the thermal low. Consequently, in the summer months the onshore flow weakens but does not reverse so that northwesterly winds continue to exist in the marine layer near the coast. The coastal region wind regime then is driven by the sea breeze circulation with weak onshore flow during the day and offshore flow at night. In this flow pattern, the marine air comes onshore during the day but without the presence of stratus; stratus does not form as the sun sets, and no fog is produced by <u>stratus lowering</u>. However, with a thin, moist layer near the ground surface and very dry conditions aloft, the stage is set for strong radiative cooling and the formation of coastal radiation fog. River valleys are particularly favored sites for this fog type and observations show that as the land breeze sets in during the night, fog is advected out over coastal waters generally to the extent of the land breeze.

Farther to sea when the marine inversion is below the LCL, local surface-based inversions are sometimes established when open-ocean marine air passes over cold water patches emanating from coastal upwelling. Fog patches can then be stimulated by subsequent passage of the cooled surface air over warmer water. The instability created by the warm water stimulates mixing to produce the initial condensation. Radiation from these shallow fog patches establishes the local inversion at fog top and further promotes local low-level instabilities, thereby producing a well-mixed layer and enhancing exchange of heat and moisture between the air and sea. The combined results of these phenomena are cooling (by radiation) of the lowest layer of air, a transfer of this secondary inversion from the surface to a slightly elevated level, the addition of moisture to the air mass, and near-adiabatic lapse conditions beneath the local low-level inversion. These processes thereby accelerate conditioning of the air mass, priming it for more persistent fog formation farther downwind, so that a fog street develops. Gradually, radiation from sequential fog patches raises the local inversion permanently off the surface. Farther downwind, these processes raise the secondary inversion to heights near that of the primary inversion and, in concert with a cessation of the northeasterly downslope winds, help to raise the marine inversion.

At the same time, as the synoptic pattern evolves so that the northeasterly winds and downward motions aloft cease, the inversion need only rise several tens of meters to above the LCL and a stratus deck forms; the thermal low becomes reestablished and the sea breeze circulation is only superposed on the basic northwesterly flow. With the northwesterly flow persisting during the night and with the marine layer being thin, long periods of extremely low visibility in fog can occur. Similar conditions of low inversion height (not to the surface) exist when weak northeasterly flow occurs in the 500-1500 m layer. Long periods of low visibility in fog also occur under these conditions.

In addition to the patterns of a long wave trough and a large-scale synoptic ridge, there is a realm of small-scale synoptic systems which occur in the 500-1500 m layer. Between occurrences of the large-scale regimes, the 500-1500 m layer is meteorologically active; highs and lows form and dissipate in, as well as move through, the coastal region. These small-scale systems can produce similar easterly flow, inversion height behavior and fog occurrence as the large-scale high pressure systems do, but over smaller areas. Likewise, small-scale lows can disrupt inversion behavior and fog occurrence patterns established by an existing large-scale ridge. Because of the horizontal scale of the smaller systems, fog occurrence and intensity vary more widely along the coast than they do with the large-scale systems.

Small-scale systems are not always accompanied by easterly flow along the coast, and fog occurrence and intensity is then related to inversion height movement caused by dynamic vertical motion alone. This downward motion is weak and the inversion is less likely to go to lower levels, in particular to the surface. Under these conditions, the inversion base is in the 100-400 m range with fog of the stratus lowering type frequently occurring.

In summary, the key factors in the occurrence of marine fog, particularly along the west coast of the United States, include (1) the open-ocean marine layer which is modified in its lowest layers by cold upwelling water along the coast, (2) adjacent patches of warm and cold water in the upwelling zone, (3) the movement and location of the semi-permanent subtropical high, and (4) the coastal mountain range. These elements combine to produce a shallow marine layer, capped by a strong inversion whose height is controlled by a balance between dynamic vertical motions aloft in the layer up to 1500 m and the thermodynamic processes within the surface marine layer. Superimposed on this general situation are the influences of downslope motion, the land/sea breeze cycle, low-level convergence patterns, the height of the lifting condensation level and radiation from condensed liquid water and coastal land surfaces. Further, dense fog seldom exceeds 400 m in total thickness; therefore, fog will not exist at a point which is more than 400 m below the base of the marine inversion unless a secondary surface-based inversion is first established.

Forecasting the occurrence of marine fog along the West Coast, therefore, requires advance knowledge of and the ability to forecast the (1) height of the marine inversion, (2) surface-850 mb synoptic and sub-synoptic systems (and by implication, the wind field in the layer up to 1500 m) and their impact on the height and strength of the inversion, (3) the height of the lifting condensation level relative to that of the inversion, (4) the potential for influence of downslope motion, the land/sea-breeze cycle and convergence patterns on inversion height, and (5) the potential for long-wave radiation from either condensed liquid water or coastal land surfaces. In the operational forecasting of marine fog, the primary questions which must be asked and answered are as follows:

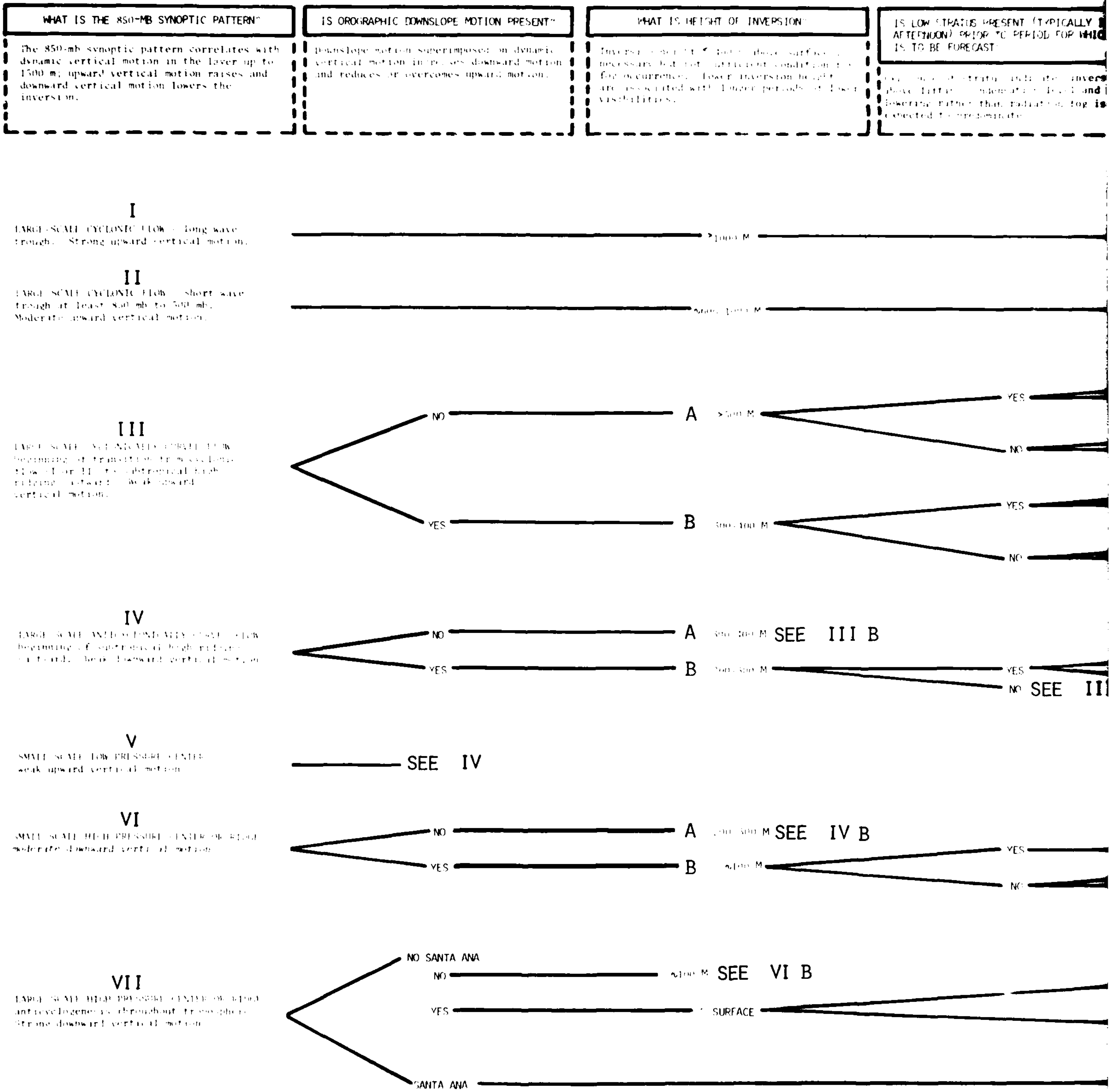
1. Is the boundary-layer wind field such that the forecast area is in the marine stratum?
2. Will the height of the inversion be above or below 400m over the forecast area?
3. Will an inversion based near the threshold height be intense enough to prevent mixing across the inversion?
4. Will the lifting condensation level be below the inversion?
5. Will middle and high altitude clouds prevent radiative cooling in the boundary layer?
6. Are there warm water patches upwind of the forecast area?

A routine designed to provide marine fog forecasts, utilizing currently available meteorological observations and forecast material to provide answers to the foregoing questions is summarized in the experimental "decision tree" presented below. The proposed "decision tree," yet to be tested in the forecasting of marine fog, is based on the assemblage of knowledge, developed by Navy-supported field studies in the 1970's, of the physics and meteorology of marine fog. No statistical base relating 850 mb patterns to fog occurrence and visibility exists. In our analyses, we have made use of the 850 mb surface because it is a routinely available chart; however, our study suggests that the 900 mb surface may be of greater utility. Further study is required (1) to develop the required statistical base, (2) to determine the ability to adequately predict the required parameters, (3) to determine the utility of an $\sim$900 mb surface, and (4) to produce new information which will fill the gaps in our knowledge of inversion behavior, heat and moisture flux across the inversion, fog morphology, fog persistence, etc. The ultimate marine fog forecast scheme must incorporate these factors and utilize numerical techniques to provide predictions of controlling parameters and processes.

The factors outlined above and incorporated in the marine-fog-forecast decision tree probably apply generally to the west coasts of most continents. The decision tree should be tested in forecast centers responsible for those areas. With some exceptions and within the context of the inversion height limitations suggested in the decision tree, the forecast concepts delineated herein probably apply to fog in other marine environs and should be tested for these situations as well.

EXPERIMENTAL DECISION TREE FOR FORECASTI

(Conditions apply to the period for which t



...R FORECASTING WEST COAST MARINE FOG

...for which the forecast is to be made.)

...RESENT (TYPICALLY IN LATE ... TO PERIOD FOR WHICH FOG ...T?	IS MIDDLE OR HIGH CLOUD PRESENT?	IS THERE HEAT AND MOISTURE FLUX ACROSS THE INVERSION?	FOG FORECAST
...tus indicates inversion is ...ensation level and stratus ...an radiation fog is ...inate.	The presence of middle or high cloud reduces net radiative heat loss and cooling of marine layer.	Strong inversions as characterized by first order discontinuities in temperature and dew point do not permit significant transport while less intense inversions often show evidence of heat and moisture flux. Downward heat flux reduces cooling of marine layer from radiative heat loss. Upward flux of moisture reduces moisture available for lowering of stratus base.	

- NO FOG
- NO FOG
- YES
  - YES — NO FOG
  - NO
    - YES — FOG NOT LIKELY
    - NO — FOG NOT LIKELY; DENSE HAZE PROBABLE
- NO
  - YES — NO FOG
  - NO
    - YES — FOG NOT LIKELY
    - NO — FOG NOT LIKELY; HAZE POSSIBLE
- YES
  - YES — FOG NOT LIKELY; HAZE POSSIBLE
  - NO
    - YES — FOG NOT LIKELY; DENSE HAZE PROBABLE
    - NO — MODERATE FOG LIKELY
- NO
  - YES — FOG NOT LIKELY
  - NO
    - YES — FOG NOT LIKELY; DENSE HAZE POSSIBLE
    - NO — COASTAL RADIATION FOG DRIFTING TO SEA POSSIBLE
- YES
  - YES
    - YES — LIGHT FOG POSSIBLE; HAZE PROBABLE
    - NO — LIGHT FOG OR HAZE PROBABLE
  - NO
    - YES — FOG LIKELY
    - NO — DENSE FOG PROBABLE
- NO SEE III B
- YES — DENSE FOG PROBABLE
- NO
  - YES — FOG NOT LIKELY; HAZE POSSIBLE
  - NO — COASTAL RADIATION FOG LIKELY, DRIFTING TO SEA; PATCHY FOG TRIGGERED BY WARM WATER PATCHES FARTHER TO SEA
- YES — (NO DATA AVAIALBLE) SHALLOW FOG PATCHES SEEM LIKELY DOWNWIND OF SHARP GRADIENTS IN SEA SURFACE TEMPERATURE.
- NO — COASTAL RADIATION FOG LIKELY DRIFTING TO SEA; PATCHY FOG TRIGGERED BY WARM WATER PATCHES FARTHER TO SEA.
- NO FOG IN REGION OF SURFACE SANTA ANA; FOG POSSIBLE FARTHER TO SEA.

Section 3
TECHNICAL DISCUSSION

This section presents the results of our investigation of the relationship between atmospheric disturbances and inversion height fluctuations and the relation of fog occurrence and morphology to inversion height along the California coast. Our investigation consisted of detailed study of marine fog episodes encountered by Calspan personnel while on field programs (from 1971-1978) under previous contracts, primarily from the Navy but also from the Air Force and the National Aeronautics and Space Administration. Fog episodes included both fog encounters by the R/V Acania (listed in Appendix A) as well as fog reported by land-based stations. Within the text of this section, specific case studies are discussed to demonstrate these relationships.

For each fog episode, twice daily radiosondes were obtained for San Diego, Vandenberg AFB, Oakland, and Medford. Hourly observations for 33 land stations (including most 24-hour stations in California) were also obtained for each episode. Finally, 3-hourly surface maps and twice-daily upper air charts at the standard levels were acquired on microfilm. These data were supplemented by observations acquired by Calspan personnel onboard the Acania and radiosondes taken at the Naval Postgraduate School in Monterey, CA, and onboard the Acania. These cases were studied and reported on by Calspan in its previous reports and publications under Navy contract (Ref. 1-3, 9, 12, 14) and a report, each, under Air Force (Ref. 18) and NASA (Ref. 19) Contract. The general areas and dates of these field studies are sketched on the chart presented in Figure 1.

Each case study is presented as an example of fog morphology and inversion height value related to a specific synoptic situation as depicted on the 850 mb chart. The 850 mb level is used because it is the standard level nearest the layer (~500-1500 m) whose circulation governs the inversion height movements which impact on the occurrence of fog. We did not have available the vertical motion fields accompanying the individual synoptic disturbances. However, vertical motion fields have been published for case studies of various kinds of synoptic disturbances. Synoptic meteorology experience based on these fields

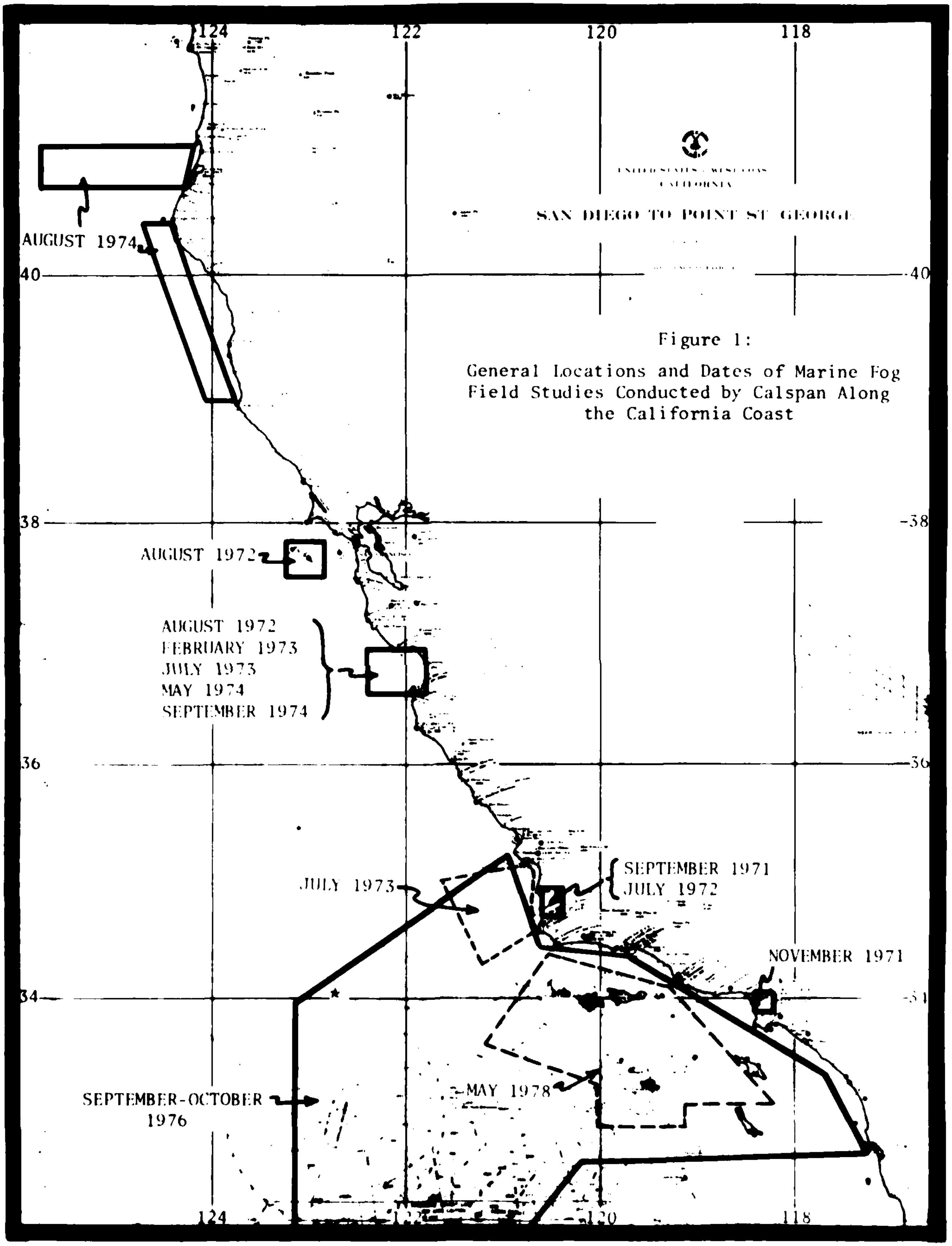


Figure 1:

General Locations and Dates of Marine Fog Field Studies Conducted by Calspan Along the California Coast and the vertical motion fields which are computed twice daily by numerical forecast models were used to assign the direction and qualitative strength to the vertical motions which are used in the following discussions.

Much mention will be made in the ensuing discussion of downslope motion and its role in lowering the inversion. Along a large portion of the California coast, the land rises to 500-1000 m within a few ten's of kilometers of the coast. Except north of Los Angeles, these mountain ranges run NNW-SSE so that winds from the northeasterly quadrant are downslope toward the coast and produce downward motion. For each fog episode, the winds from surface to 1500 m were plotted from the radiosonde observations. In all cases in which the inversion was between 100 m and sea level, northeasterly flow was present at the levels which would produce downslope motion.

Synoptically, the combination of northeasterly flow and very low inversion heights frequently accompanies high pressure systems at 850 mb. It appears that the superposition of downslope motion on the dynamic downward motion of the high pressure system produces total downward motion strong enough to drive the inversion to very low levels and occasionally to the surface. Analysis of wind soundings for all the fog episodes shows that with a wind direction which can produce downslope motion, the inversion height qualitatively behaves consistently with a superposition of the two types of vertical motion.

The superposition is most strikingly demonstrated for small-scale high pressure systems when the wind is downslope at VAN but not at OAK. Under these conditions, the inversion height at VAN will be lower than at OAK. Similar variations in inversion height related to downslope motion occur with low pressure systems. In this case, the downslope motion may balance or even overcome the dynamic upward motion, and lead to an inversion height below 400 m and possibly fog in an otherwise general situation of high inversion [above 400 m] and no fog.

3.1 Inversion Time Series for July 1972

San Diego

As an introduction to our detailed technical discussion, consider the inversion height fluctuations for July 1972. Figure 2 shows the time series of inversion height at San Diego using the 1200 GMT observations. Inversion height exhibits a diurnal variation primarily due to the sea breeze circulation; including this small amplitude variation by also presenting 00 GMT observations would only mask the large amplitude, long wavelength variations in inversion height which are related to synoptic disturbances. Note that the ground surface for the San Diego radiosonde is at 125 m (msl).

The month began with a low pressure system located off the coast of California (Figure 3a). With weak upward motion, the inversion was in the 500-700 m range. During the 3rd-5th, a small-scale high cell moved north-northwestward along the coast to southwest of San Diego (Figure 3b). The downward motion associated with this high cell lowered the inversion to 200 m (4th-5th). During the next ten days, there was a slow evolution to large-scale cyclonic circulation and the inversion climbed to above the 600 m level on the 16th (Figure 4c).

During the 18th-22nd, a long-wave trough was located off the West Coast with cyclonic circulation in the low levels (Figure 4d). Correspondingly, with deep upward motion, the inversion rose to high levels, reaching 1200 m on the 20th. The long-wave trough was replaced by a short-wave trough on the 23rd-25th. With weak cyclonic flow at 850 mb (Figure 5a), the inversion dropped down to near 400 m. The short-wave trough moved out and a series of small-scale highs were present near San Diego from the 27th-30th (Figure 5b-5d). The dynamic downward motion augmented by downslope motion drove the inversion down to (at and near) the surface during these four days.

The minimum visibility for each day is plotted across the bottom of Figure 2. A comparison between the minimum visibilities and the inversion height reflects the general relationship between inversion height and fog. The highest visibilities of 12 mi occur with the highest inversion heights

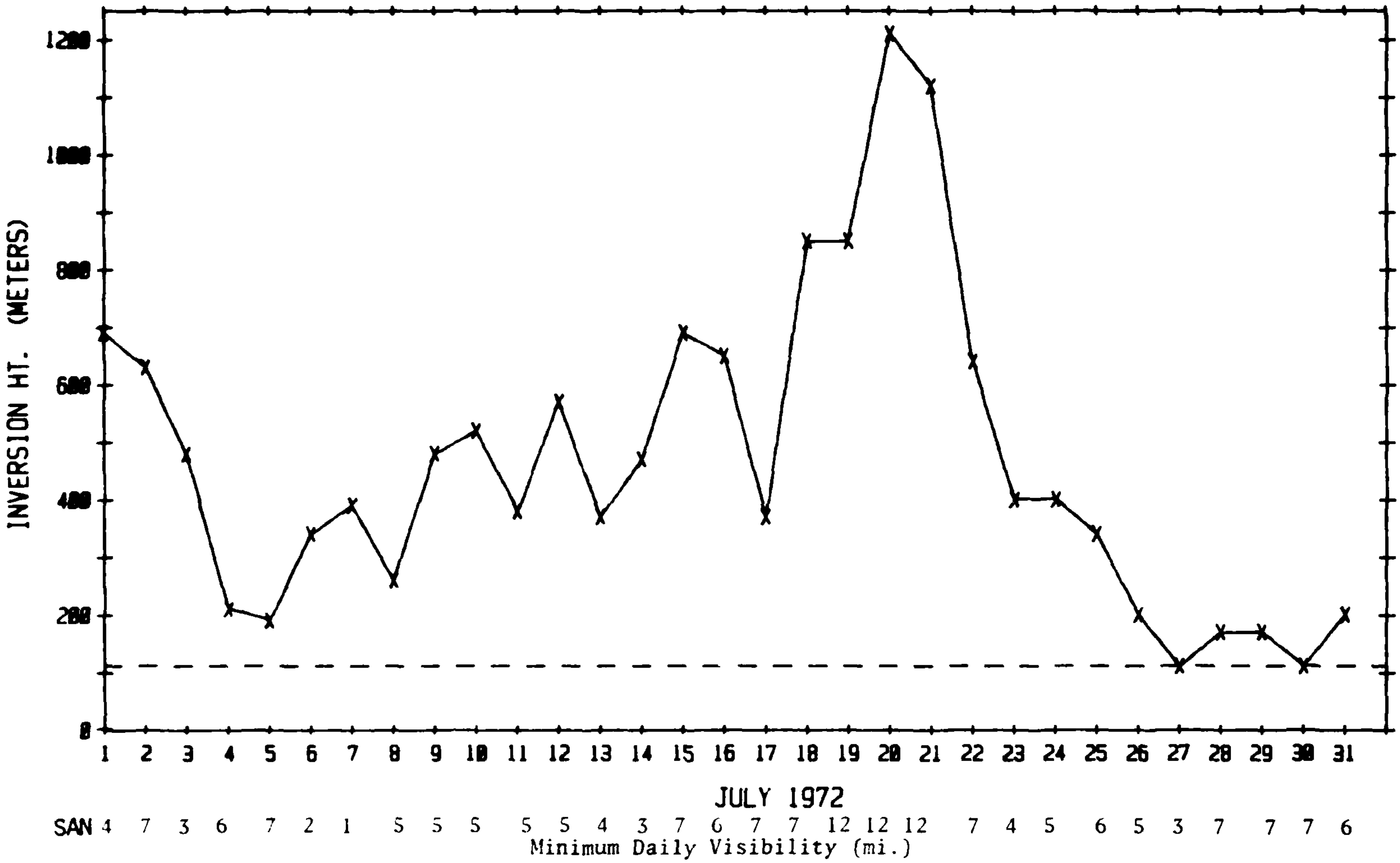
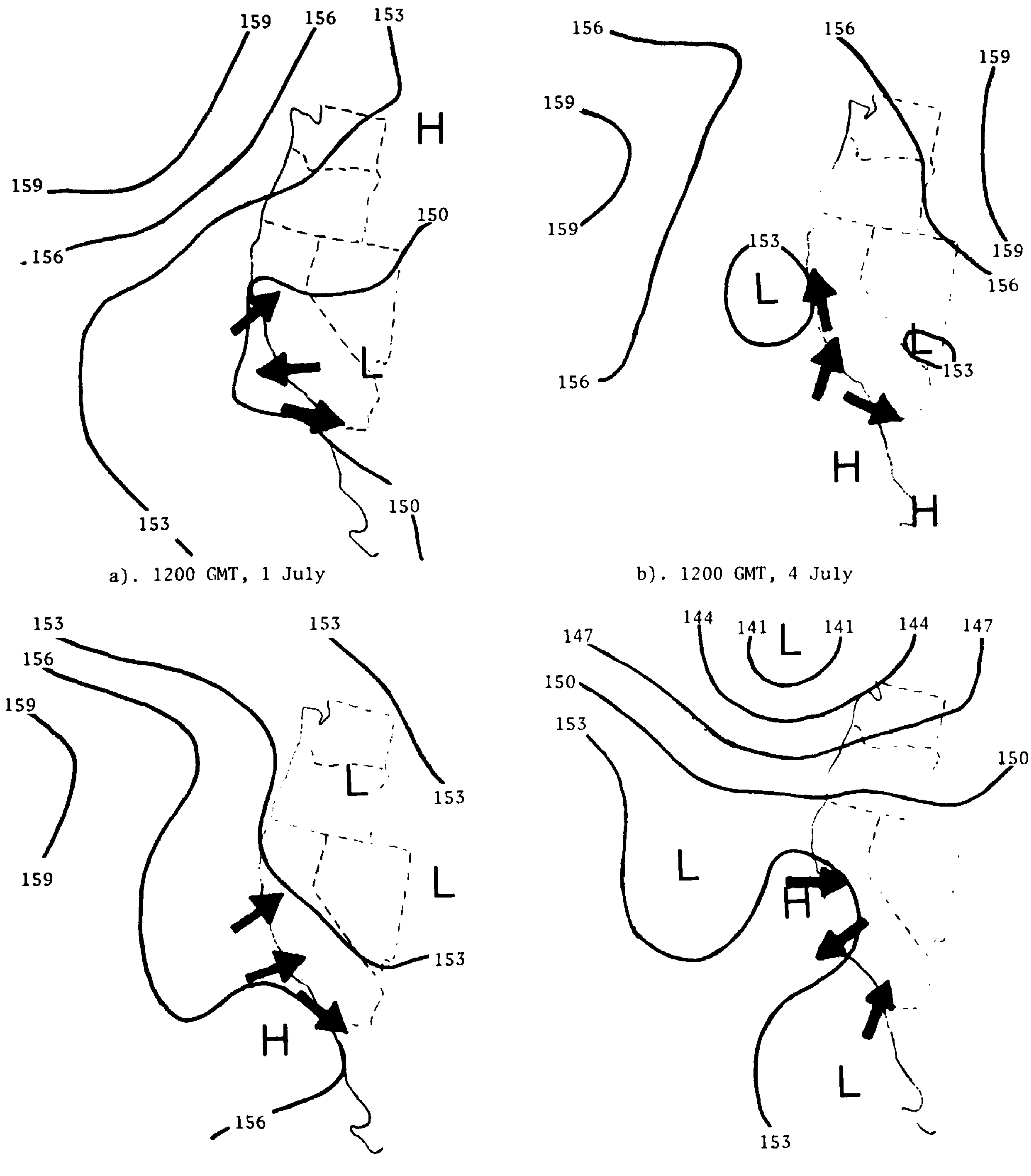


Figure 2. Inversion Height Time Series and Minimum Visibilities (miles) for San Diego,CA July 1972. Dates Indicate 1200 GMT. Dashed Line Shows Surface Elevation of Radiosonde Observation. Visibilities Measured at 17m (msl).



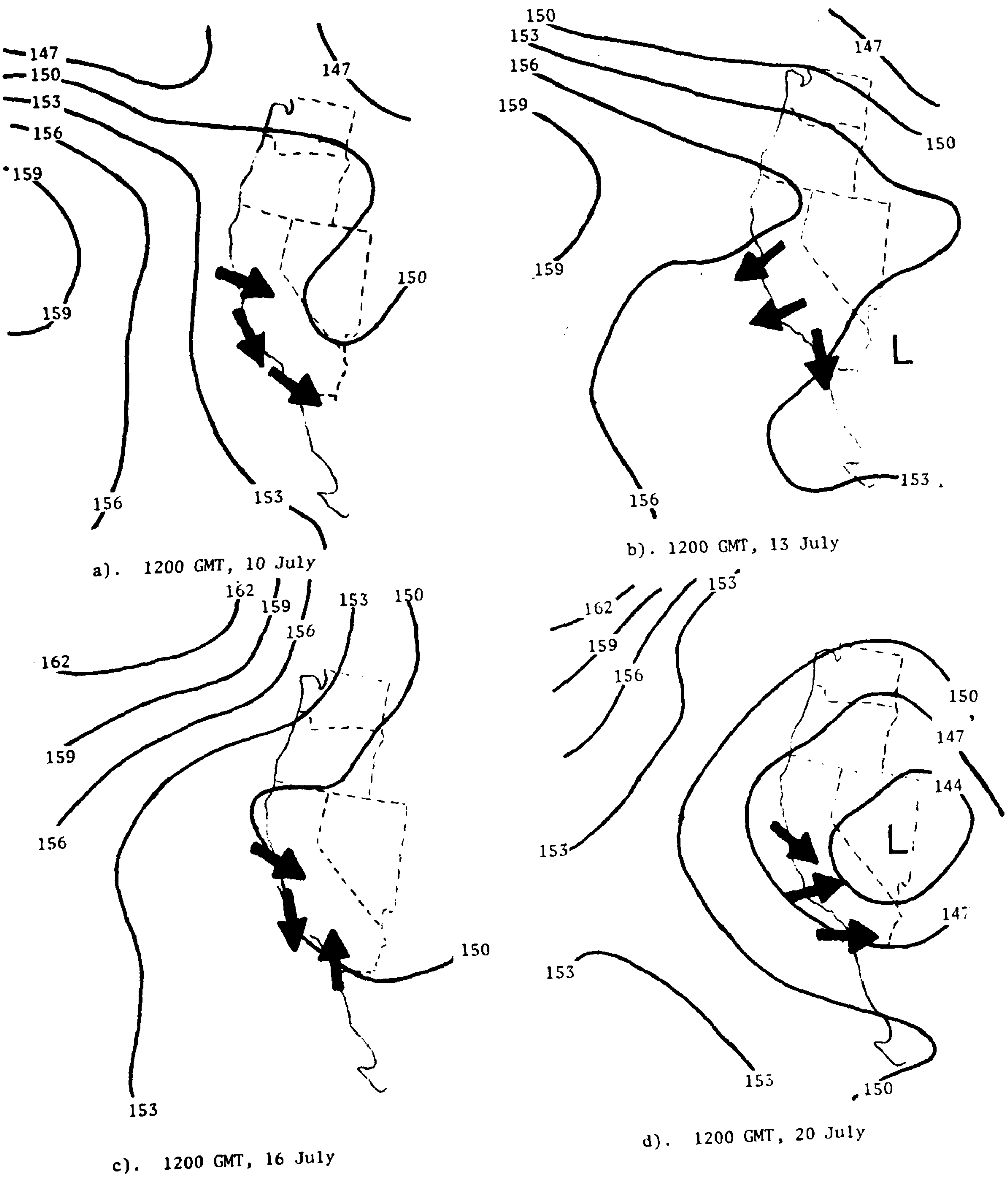
a). 1200 GMT, 1 July

b). 1200 GMT, 4 July

c). 0000 GMT, 6 July

d). 1200 GMT, 8 July

Figure 3. 850-mb Charts for Selected Days 1-8 July 1972. Arrows Show Wind Direction North to South for Oakland, Vandenberg AFB, and San Diego, CA.



a). 1200 GMT, 10 July

b). 1200 GMT, 13 July

c). 1200 GMT, 16 July

d). 1200 GMT, 20 July

Figure 4. 850-mb Charts for Selected Days 10-20 July 1972. Arrows Show Wind Direction North to South for Oakland, Vandenberg AFB, and San Diego, CA.

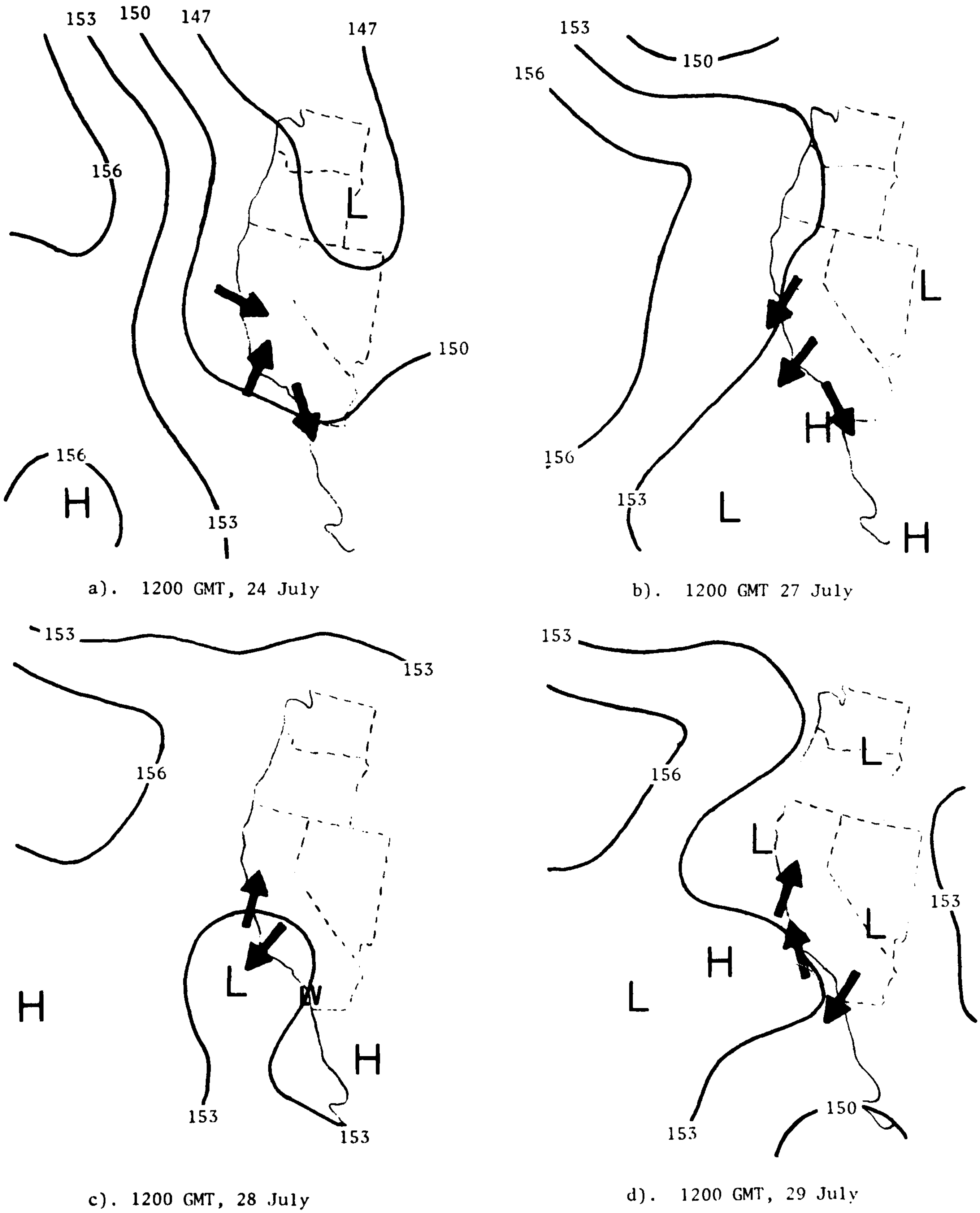


Figure 5. 850-mb Charts for Selected Days 24-29 July 1972. Arrows Show Wind Direction North to South for Oakland, Vandenberg AFB, and San Diego, CA.

(20th to 21st) and the lowest visibilities on the 6th and 7th occur with heights below 400 m. There is also a tendency for visibilities in the 3-5 mi range to occur with inversions in the 400-500 m level (9th-14th, 23rd and 24th).

The visibility behavior for the month of July 1972 for San Diego is summarized in the following table:

Table 1

Minimum Surface Visibilities as a Function of 1200 GMT Inversion Height Above the Surface at San Diego, July 1972

Minimum Visibility (mi)	1	2	3	4	5	6	7	12
Days with:								
Inversion above 400 m			2	1	3	1	4	3
Inversion below 400 m	1	1		2	5	3	5	

Of the 14 days with inversion above 400 m, there were no days with visibility below 3 mi. Seven days had a visibility of 7 mi or greater; three of these days had a minimum visibility of 12 mi. Of the 17 days with inversion below 400 m, the minimum visibilities were all at 7 mi or lower with the two lowest visibilities of the month (at 1 and 2 mi) occurring in this data group.

For the inversion below 400 m, 13 of the days fell within the 5-7 mi visibility range. Examination of the radiosonde data for these days shows a tendency for the dewpoint which is characteristic of the marine layer to extend somewhat above the inversion base. This feature suggests exchange of moisture and heat through the inversion which could prevent fog formation from the stratus lowering process. This type of situation requires further investigation, perhaps through Deardorff's exchange model, to determine the role of transfer across the inversion in fog occurrence.

Vandenberg and Oakland

In the previous subsection, we investigated the inversion height behavior as a function of atmospheric disturbances for San Diego (SAN), the southernmost U.S. station along the coast. Now consider inversion behavior for July 1972 at Vandenberg (VAN) and Oakland (OAK), stations which are progressively farther north along the coast. The inversion time series for these two stations are shown in Figure 6 with the same format as before; the dashed curve represents Oakland's data. For Oakland, the surface observation is at sea level whereas at Vandenberg it is at 100 m. At the bottom of the figure, minimum visibility data are shown for VAN and Monterey (MTY).

Comparison of the San Diego inversions with those at VAN and OAK shows that when a long-wave feature controls the inversion height (18th to 22nd) the inversion height along the coastal region behaves similarly; in this case, the heights rise to around 1200 m. However, when smaller scale systems control the inversion height, two of the stations may be in phase, as OAK and VAN on 13th and 14th and 27th to 29th, and VAN and SAN on 4th and 5th. Additional insight into how synoptic disturbances affect the height of the inversion can be gained from a brief discussion of the OAK and VAN time series.

On the 1st, both OAK and VAN were in transition from anticyclonic to cyclonic circulation with inversions in the 200-300 m range (Figure 3a). Both inversions then rose in response to a low pressure center off the coast (Figure 3b). Oakland's inversion stayed at 700 m (4th to 6th) as the low weakened but remained near OAK. During this same period, VAN's inversion height was in phase with San Diego's, but the inversion did not descend as low at VAN as at San Diego since VAN was in the transition zone between the high and low (Figure 3c).

On the 8th, this inversion lowered to 100 m (above sea level) at VAN while at OAK it only lowered to 200 m. These two stations were under the influence of a high located between the two stations (Figure 3d). The inversion lowered at OAK in response to the dynamic downward motion associated with the high which produced westerly flow at OAK and northeasterly flow at VAN between 1500 m and the inversion base. At VAN, the inversion was forced lower because of the additional effect of the downslope motion associated with the easterly flow.

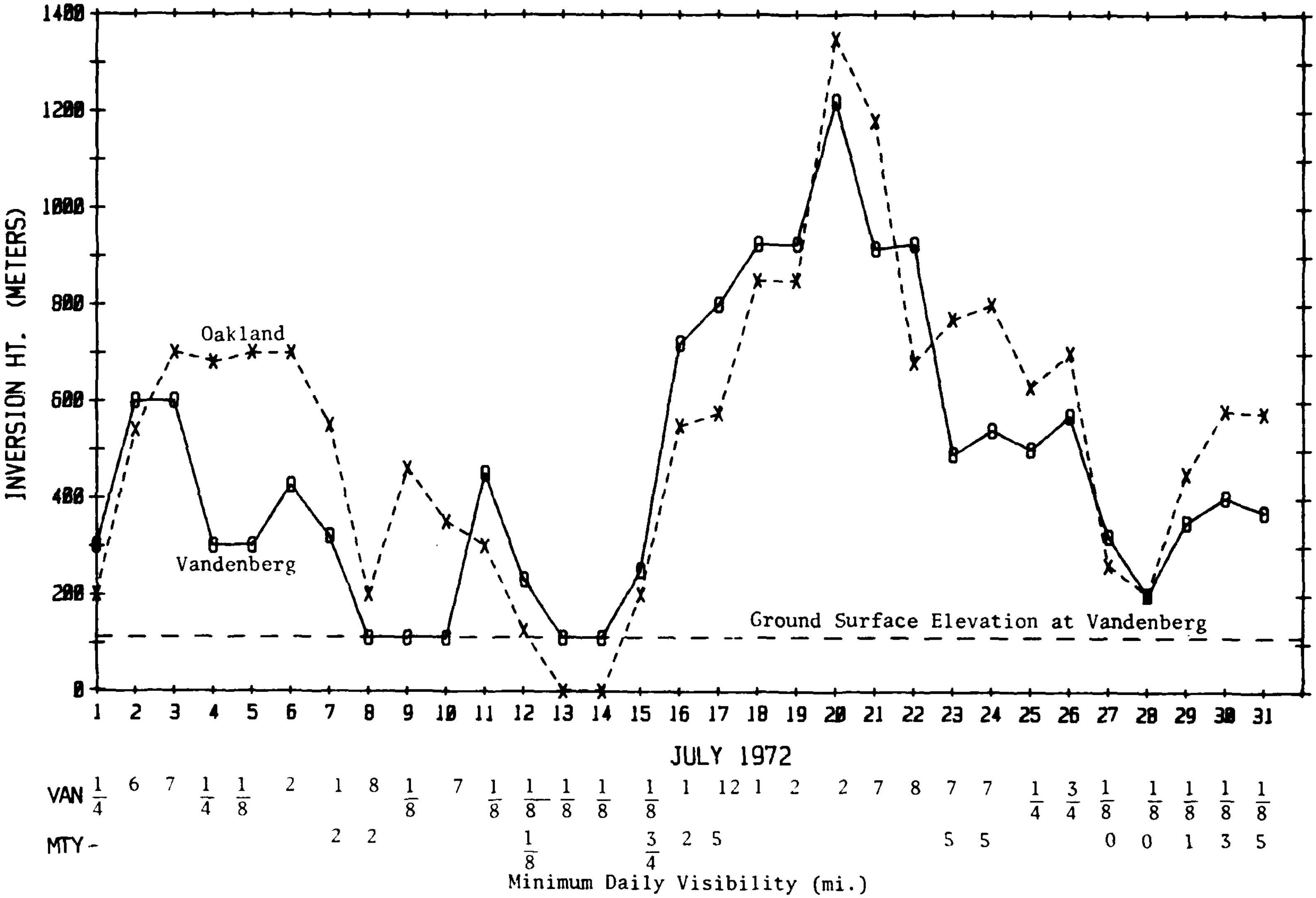


Figure 6. Inversion Height Time Series for Oakland, CA (dashed line) and Vandenberg AFB (solid line); Minimum Visibilities for Vandenberg AFB and Monterey, CA, July 1972. (Dates indicate 1200 GMT)

On the 10th, the inversion lowered to 100 m at VAN while it remained near 400 m at OAK. No small-scale high pressure system was detected at 850 mb (Figure 4a). However, the winds at VAN were easterly in the layer 300-1000 m while they were westerly at OAK. Thus, downslope motion from easterly winds produced by the flow pattern below 850 mb was responsible for the localized lowering of the inversion at VAN.

On the 13-14th, the inversion lowered to the surface (sea level) at OAK and the surface (100 m) at VAN. Easterly flow existed at both stations on these days in response to the large high pressure ridge extending NE-SW across Oregon and Washington (Figure 4b). This ridge was the 850 mb response to long wave anticyclogenesis which took place throughout the troposphere. At 850 mb south of the ridge, a low existed east of San Diego. Thus, San Diego's inversion (Figure 2) was near 400 m while farther north in the easterly flow, the inversion was at or very near the surface.

The inversion at OAK and VAN then rose to above 1200 m on the 20th in response to the long wave trough already mentioned (Figure 4d). With the short wave trough (Figure 5a) that followed, the inversion was in the 500-700 m range (23rd-26th).

On the 27th, both inversions drop about 400 m to 300 m, then drop farther to 200 m on the 28th, recovering on the 29th to near 400 m. Between the 26th and the 27th, a weak ridge built onshore over northern California producing a shift from westerly to northerly and north-northeasterly flow over the central California coast (Figure 5b). The ridging and the downslope motion caused the inversion to lower on the 27th. On the 28th, a mesoscale low appeared south of VAN (Figure 5c) and the wind shifted to northeasterly and increased in speed, thus increasing the downslope motion and driving the inversion down to 200 m. Such a strong downslope would drive the inversion to the ground in anticyclonic conditions; apparently in the cyclonic flow, the downward motion from downslope was counteracted by weak upward motion and the inversion did not descend to the ground.

On the 29th to 31st, the mesoscale low moved north of OAK (Figure 5d) and the stations were back in the onshore flow and weak upward motion associated with the low pressure system. The inversion rose to 400-600 m, with the higher value at OAK which was nearer the low center where the upward motion was probably stronger.

The foregoing discussion shows how the inversion height varies with synoptic situations spanning the spectrum from long wave systems down through both large and small scale systems. There is a qualitative correlation between scale of atmospheric system and inversion height. For low pressure systems, the long wave trough produces inversions of 1000 m and higher, short wave troughs and synoptic scale lows have inversions in the 500-800 m range, and the smaller scale synoptic lows are associated with inversions around 400 m. For high pressure systems, the small scale high has inversions in the 200-400 m range. The inversion height related to high pressure associated with a long wave anticyclonegenesis is difficult to determine since these situations are accompanied by northeasterly flow and downslope motion which drives the inversion to the surface.

These relationships of inversion height to scale of atmospheric disturbance are not based on a thorough statistical study but they can serve as guidelines for fog forecasting until a more complete statistical study is carried out.

The individual synoptic cases for July 1972 will be discussed in detail in the subsequent section. Before proceeding to those discussions, an overview of fog morphology as a function of inversion height along the central California coast is presented.

The daily minimum visibility at Vandenberg (elevation 100 m) is presented across the bottom of Figure 6. A couple of features of the VAN observations stemming from the 100 m height of the observation station need to be pointed out. First, in a stratus lowering fog, an inversion height above sea level of 500 m is required for the inversion base to be 400 m above the surface. Secondly, when the inversion is at the surface at 100 m, it may not have descended to sea level and the marine layer may be present from sea level to 100 m.

On only eight days was the minimum visibility at or above 7 miles, and on seven of these days the inversion was above 500 m (msl). Of the 19 days when the minimum visibility was below 1 mile, 16 of them had an inversion height less than 400 m above the ground. On two of the other three days (25 and 26 July) the inversion was just a few 10's of meters above 500 m (msl) and the visibility was below 1 mile for less than 2 hours, occurring during the few hours before sunrise. These two fogs were cases of stratus lowering when the stratus base just managed to lower to the surface at the end of the night because the marine layer was just slightly thicker than 400 m. Thus the 400 m threshhold for fog occurrence held true for VAN for this time series.

Table 2 shows minimum visibility versus inversion height above the ground for the days with visibility below one mile. Approximately 75% of the 1/8 mi visibilities occur with an inversion height of 200 m or less. Both cases with visibility greater than 1/2 mile occur with an inversion above 300 m. A minimum visibility of 1/4 mile shows a tendency for the intermediate inversion heights.

An interesting feature of fog morphology is the length of time during a fog episode that the visibility remains at various values as a function of inversion height. Table 3 shows the percentage of hours that the visibility was at the indicated value as a function of inversion height for Vandenberg for July 1972. Note the tendency for most hours of low visibility to occur with low inversion height: for 0 height, all hours are $\leq$ 1/4 mi and for 100-200 m, 89% of the hours are $\leq$ 1/4 mi. With the higher inversions, the majority of fog hours shifts to higher visibility values.

From the standpoint of stratus lowering process, this tendency makes sense. With the lower inversion, cooling can bring the stratus base to the ground more quickly in the late afternoon. With respect to the observed lower visibilities, at least three processes may contribute to this condition:

1) increased liquid water from the radiational cooling now operating on a shallower layer;

2) evaporation of fewer of the small drops in turbulent downdrafts because of the shorter travel distance between drop generation at cloud top and the surface;

3) presence of higher concentrations of condensation nuclei in the easterly continental winds at fog top.

These factors require further investigation and a larger data sample than is currently available.

Table 2

Minimum Visibility vs. Inversion Height (Visibility <1 mi)

Vandenberg, July 1972

Inversion Height Above Ground	Min. Visby. (mi) 1/8	1/4	5/8-7/8	Obs
0	2			2
100	3			3
200	2	2		4
300	4	1	1	6
400		1	1	2
Obs	11	4	2	17

Table 3

Percentage of Hours at Indicated Visibility when Visibibity <1 mi

Vandenberg, July 1972

Inversion Height	Visibility (miles) 1/8	1/4	1/2	3/4	Total Hours
0	67	33			32
100-200	50	39	11		27
200-300	13	40	37	10	20
300-400	33			67	3

Monterey is the next station along the coast north of VAN and south of OAK, and its fog behavior versus inversion height was also investigated. Only the minimum visibilities below 6 miles for Monterey are shown in Figure 6. Because of the noncoincidence in space between the surface visibility measurement and the inversion height measurements, only a qualitative discussion of Monterey's fog morphology is presented. The lowest visibilities occurred on the 27th and 28th and 12th and 15th when the inversion at both stations was at 200-300 meters.

Making the assumption that fog behavior on the 29-31st at Monterey was related to the Oakland inversion height (an assumption which is supported by the synoptic situation which suggests both OAK and MTY are under the influence of the same synoptic system, Figures 4b and 4c), then the gradual increase in visibility (1, 3 and then 5 mi) qualitatively relates to the increase in inversion height (450, 500 and 600 m). A similar sequence of visibility vs inversion height can be seen at Monterey on the 16th and 17th. This relationship, in this case of stratus clouds, is consistent with a recent Calspan study for the Army (Rogers and Hanley, 1980) which demonstrated the reasons for increasing visibility with distance from the stratus base in the haze beneath a stratus cloud. Applying this result to visibility beneath stratus clouds which do not lower to the surface (inversion above 400 m), we would expect that the visibility would be directly related to the height of the inversion.

3.2 Examples of Fog and Inversion Behavior for Various Types of Synoptic Systems

In these discussions, we will describe changes in the flow in the layer surface-to-1500 m, with emphasis on the layer 500-1500 m. As described in the summary, the surface pattern only responds, and then only very slightly, to the pattern changes which occur at levels immediately above the surface. Changes of the 850 mb flow are a good representation of the changes in the levels below 850 mb particularly with large-scale synoptic systems. However, with some of the small-scale systems, the changes are better defined in the layer below 850 mb. In those cases, reference will be made to the time sequence of vertical profiles of wind at radiosonde stations.

Long Wave Anticyclogensis Producing Easterly Flow in 500-1500 m Layer

Figure 7 shows 1200 GMT (0500 PDT) 850 mb charts for 3 and 13 July 1972. The pattern on the 3rd is representative of a large-scale trough and shows low pressure off the coast with southerly winds at OAK and VAN. The layer down to the surface also has southerly winds. The base of the inversion was in the 600-700 m range and minimum visibilities along the coast from Vandenberg to San Francisco were 7 mi* or greater. Stratus was present during the nighttime hours, but the lowest base was observed at ∿275 m. Surface flow was westerly with wind speed increasing during the day and decreasing at night due to the superposed sea breeze circulation. This is a typical scenario for a large-scale trough with the marine layer too thick for the base of the stratus cloud to propagate to the surface during the night to produce fog.

The flow pattern on 13 July is representative of semi-permanent high pressure circulation aloft. At 850 mb, an east-west high pressure ridge extends onshore over northern California with northeasterly flow over the coastal region from Vandenberg to San Francisco. At Vandenberg, the winds have a large easterly component from 850 mb (1500 m) all the way down to 300 m (msl).

The Vandenberg AFB sounding site is based at 100 m, thus, the temperature structure in the lowest 100 m in unknown. The radiosonde data indicate that the inversion is down to very near 100 m. At this time, Calspan was participating in a field study of fog in the Vandenberg area for the Air Force. The observation site was 10 km southwest of VAN and ∿1 km inland at an elevation of 85 m. Our data showed that the marine layer extended up to 140 m with fog and stratus cloud from 85-140 m. In this case, the downslope motion was not able to drive the inversion down to sea level or below the lifting condensation level in the marine layer. Thus, we have the situation of a shallow marine layer with a stratus deck; the resulting fog is longlasting with very low visibilities.

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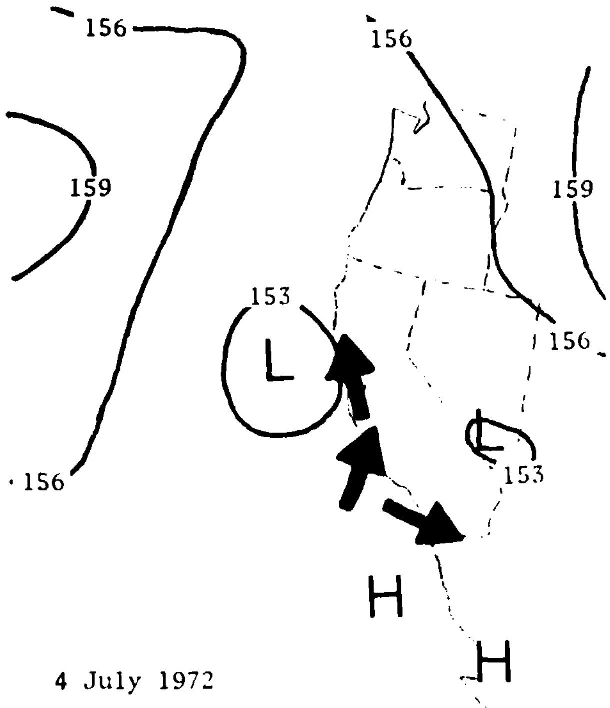
*In reference to visibility, winds and temperature, English units are used throughout the text of this section to facilitate comparison with NOAA WBAN data and charts.



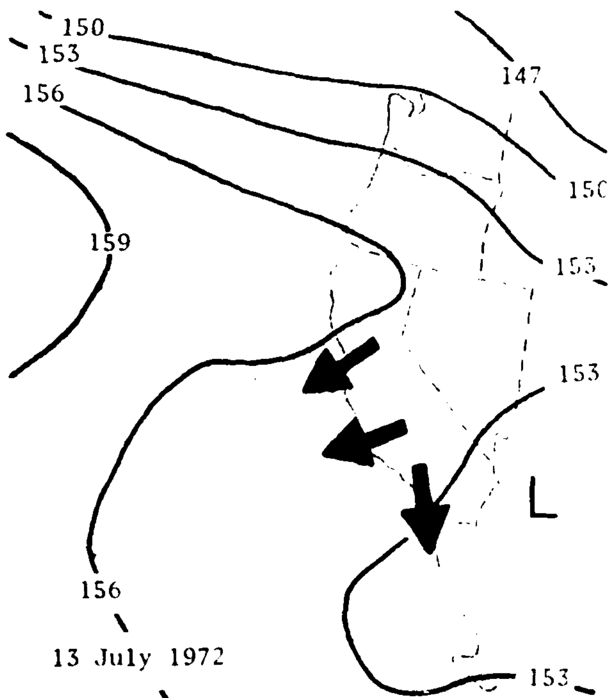


Figure 7. 850-mb Charts for 1200 GMT, 4 July and 13 July 1972.

At Vandenberg AFB, the visibility on the night of 12-13 July was below 1/2 mile for 13 consecutive hours and at 1/8 mile for 11 of those hours. At 85 m-msl, Calspan instrumentation measured minimum visibilities of the order of 800-900 ft (250 m) during the fog. Continuous wind direction records at 140 m showed two periods of northeast wind during the night of 12-13 July as the land breeze developed. During both of these periods, the visibility improved as the air from farther inland moved back toward the coast. Such visibility improvements are characteristic of low inversion fogs during which the land breeze occurs.

By 1200 GMT on the 14th, the inversion was definitely down to the ground (at least 100 m). Instrumentation at the field showed a wind shift from northwesterly to northeasterly at 0900 GMT, with a simultaneous disappearance of the fog and stratus. Simultaneously, the air temperature at 85 m increased by 5°F indicating that the inversion had lowered below the 100 m level. However, the inversion apparently did not descend to sea level. After six hours of clear sky, the wind swung into the southwest, and visibility of 1/8 mile again prevailed.

Although in this case the inversion did not descend to sea level in the Vandenberg area, farther north at Monterey it did come down to sea level. As seen in Figure 6, the inversion was at the surface at OAK on both 13 and 14 July. On neither day did the visibility at Monterey (MTY) drop below 7 miles. Skies were clear with no reports during the day of "fog bank or stratus to the west," a typical comment in the WBAN observations when the stratus deck is present. The wind on both days was light and variable but mostly from the north and east. These conditions are directly opposite to days when the marine layer is present when the flow is moderate westerly. Maximum temperature for both days was near [illegible] F compared to marine layer days when the temperature rarely rises above 7[illegible] F. All these observations show that the flow patterns were such that the inversion was at sea level and the marine layer was prevented from coming onshore.

On 12 and 15 July, either side of the period when the inversion was at the ground, the inversion remained below [illegible] m at OAK, and Monterey experienced fog. On the 12th, the visibility was 1/8 mi between 01 and 07 PST and on the

15th, it was 3/4 mi between 05 and 06 PST. Conditions on the 12th were typical of the marine environment as the inversion was lowering to the ground from near 400 m. During the 11th, the surface flow was onshore, the maximum temperature was near 70°F, and a fog bank was continuously observed to the west.

On the 15th, conditions were typical of a reestablishment of the marine layer after the inversion was at low levels. Surface winds were variable with frequent periods of easterly flow; the maximum temperature was near 80°F. The marine layer was being reestablished to a depth in which stratus and fog could occur in the evening hours of the 14th as shown by recurrence in the observations of "fog bank to the west." The minimum visibility was only 3/4 mi and only of short duration as fog occurred when the inversion was rising rapidly (Figure 6) and in a marine layer which was modified somewhat by mixing with the warm air.

This case shows how the inversion is driven to low levels by downslope motion in easterly flow in the layer up to 1500 m. The easterly winds were produced by ridging in the low levels in response to development of the semi-permanent high in the middle and upper levels. Where the downslope motion was strongest, the inversion was driven down to sea level along the coast. The accompanying light easterly surface flow kept the marine layer to sea, and two days without fog occurred. Where the downslope motion was weaker, the inversion did not lower to sea level. In this case, fog occurred but its hour-to-hour intensity was correlated with wind direction. Although the inversion did not descend to sea level, the large scale surface pressure pattern was weakened so that the sea breeze circulation predominated. Therefore, an easterly land breeze occurred at night, and the visibility improved during that time.

Offshore Atmospheric Structure During Periods of Extremely Low Inversion

When the inversion is at the surface on shore and warm air from above the inversion is present onshore, the marine layer is still present not very far to sea. In addition, the clear area off the coast is not from warm dry air displacing the marine layer but rather a result of the inversion descending below the lifting condensation level of the marine layer. Calspan was aboard the Acania in October 1976 (CEWCOM 76) during a period of strong easterly flow and extremely low inversion, and the following discussion documents the characteristics of the marine layer and the warm air which occurred during that episode.

Anderson (1951) reported that in times of Santa Ana conditions with strong offshore winds (gusts to 35 mph), westerly winds were found 10-20 miles offshore. The implication is that the marine layer is present at this distance from shore. The Acania was in the Santa Barbara Channel late on 7 October 1976. The 850 mb chart for 00 GMT 8 October (Figure 5a) shows northeasterly flow at both VAN and San Diego. The surface map for 00 GMT on the 8th (Figure 5b) shows high pressure to the north over the land. While approaching the coast near Santa Barbara late on the 7th, the Acania encountered strong, very warm northwest winds a few miles off shore. While crisscrossing the region, we found that the warm air was a jet which was coming through a mountain pass along the shore. When the area of initial encounter with the jet was passed through a couple of hours later, the jet was no longer there. With this jet-like structure, it appears that the Santa Ana, while strong and gusty onshore, quickly loses its momentum through horizontal mixing and through movement away from the region of strong pressure gradient onshore. The distance to which an individual Santa Ana can push to sea seems to depend on the strength of the pressure gradient along the coast.

During the 8th, the Acania continued its investigation along the California coast and at 0130 GMT on the 9th started westward to sea from just offshore at Vandenberg. An acoustic sounder onboard the Acania provided measurements of the height of the inversion base. (Comparison of the inversion height measured by the acoustic sounder to that obtained from radiosondes on the Acania showed the same height value, within the accuracy of the two systems.) The time sequence of the inversion height showed that at no time between 00 GMT and 12 GMT did the inversion lower to the surface over the ocean, and skies were clear over the Acania. Onshore, Vandenberg was clear, and no mention of fog offshore was made in the observations. Although the inversion was above sea level, no stratus or fog was present as the lifting condensation level was above the inversion as shown by the Acania surface temperature and dewpoint data for the period.

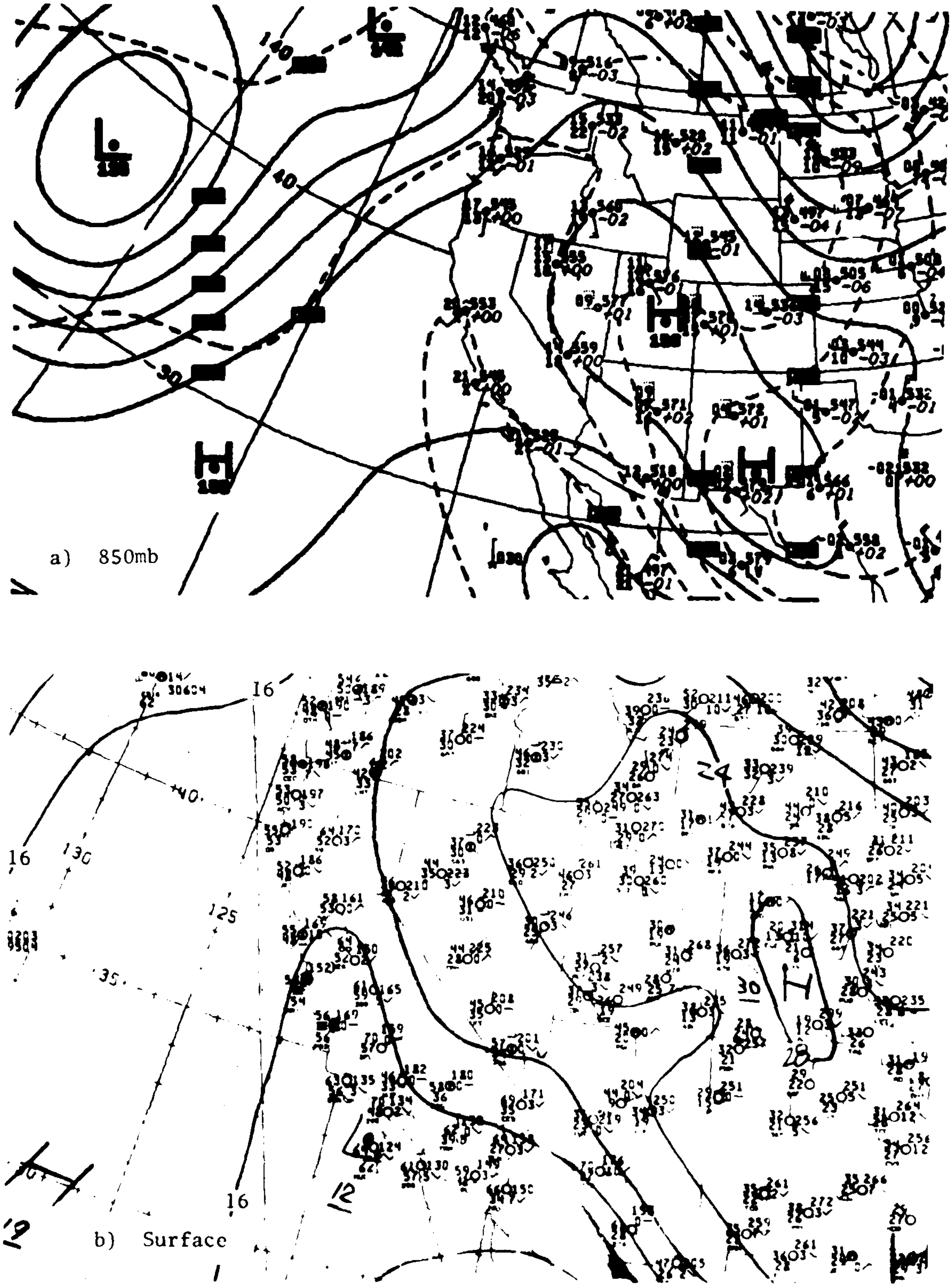


Figure 8 Surface and 850 mb Charts for 1200 GMT, 8 October 1976.

At 00 GMT, Vandenberg reported the inversion base at 200 m and at least to 100 m by 1200 GMT. Radiosondes taken aboard the Acania showed a 200 m inversion 30 nmi west of VAN at 05 GMT and a 100 m inversion at 11 GMT at 40 nmi. Thus, the inversion, at least out to 40 nmi from shore, was behaving in the same manner as at the shore. Based on this analysis, we interpret the time history of inversion height from the moving Acania as if it were measuring at a fixed point in space. At 06 GMT, the inversion base was at 200 m and remained there for a couple of hours until it started downward at 08 GMT and reached a minimum of 100 m at 12 GMT. Between 00 GMT and 12 GMT, the wind at VAN shifted to an easterly component from the surface up to 900 m. The resulting downslope motion apparently drove the inversion down to the 100 m level 40 nmi out to sea as well as onshore.

The period 1200-2100 GMT was analyzed in Mack et al (1977) and showed the appearance of a stratus deck as the inversion rose above the lifting condensation level at 1500 GMT. The satellite picture for this day showed that the region off the west coast, which on the previous day had been mostly cloud-free, was now cloud covered. Thus, on the 8th the inversion was below the LCL and the area was cloud free; then a 100 m rise in the height inversion raised the inversion above the LCL and a stratus deck covered the area. But during the entire period, the marine layer was present over the ocean.

At 00 GMT on 10 October, the Acania reached its westernmost point approximately 90 nmi offshore; and then during the night returned to the coast on an ENE track. During this 12 hour period, the inversion base remained nearly constant at 300 m, coinciding with the inversion measured on shore. Overcast stratus was observed along the entire track, but the stratus did not lower to the surface during the night.

The reason that fog did not form cannot be pinpointed, but several features of this situation suggest a possible mechanism for suppressing fog formation. During the entire ENE leg of the cruise track, the air was colder than the water. The difference varied from as little as 0.5°F to as much as 5°F as the air was passing over eddies of cold and warm water. The air was heated from below and was convective and turbulent.

The two soundings taken during this track show that the coldest temperature at the top of the marine layer was accompanied by moderate relative humidity (70%) rather than the humidity (near 100%) which is usually found at the top of the stratus deck. This observation suggests that the strong turbulence from the heating was allowing the marine layer to penetrate into the dry air above the inversion. The resulting mixing apparently reduced the effect of the radiational cooling on the marine layer and prevented the stratus lowering from occurring. This process requires further study, possibly through Deardorff's inversion model (1979).

Coastal Radiation Fog

Another type of fog that has been found to occur with very low inversions and with surface inversions on shore has been labeled "coastal radiation fog." This fog has been observed and studied in the Monterey Bay area during three separate cruises on the Acania. The 850 mb charts for 1200 GMT 25 and 26 July 1973 are shown in Figure 9. The northeasterly flow of the 25th associated with the large scale NE-SW ridge gives way on the 26th to lighter northeasterly winds associated with the small scale low pressure system to the south. The inversion at VAN is down to 100 m on both days; radiosondes taken at MTY at 15 GMT show an inversion near 100 m on both days.

The characteristics of this type of fog have been documented and discussed in Ref. 2 and 3. These studies have shown that during the early morning hours the fog moves out into the bay on easterly winds in the vicinity of a river mouth. This behavior is consistent with the weak onshore gradient in these low inversion situations and the predominance of the sea breeze circulation, especially the land breeze at night.

Observations have also shown that the fog tends to come back onshore with onshore winds which occur toward sunrise. Observations at MTY airport support the occurrence of fog on shore later in the night for many of the coastal radiation fogs. The airport is at the southern end of Monterey Bay and south of the rivers which empty into the bay. On the 25th and 26th of July, no westerly wind occurred at the airport before dawn, and fog did occur

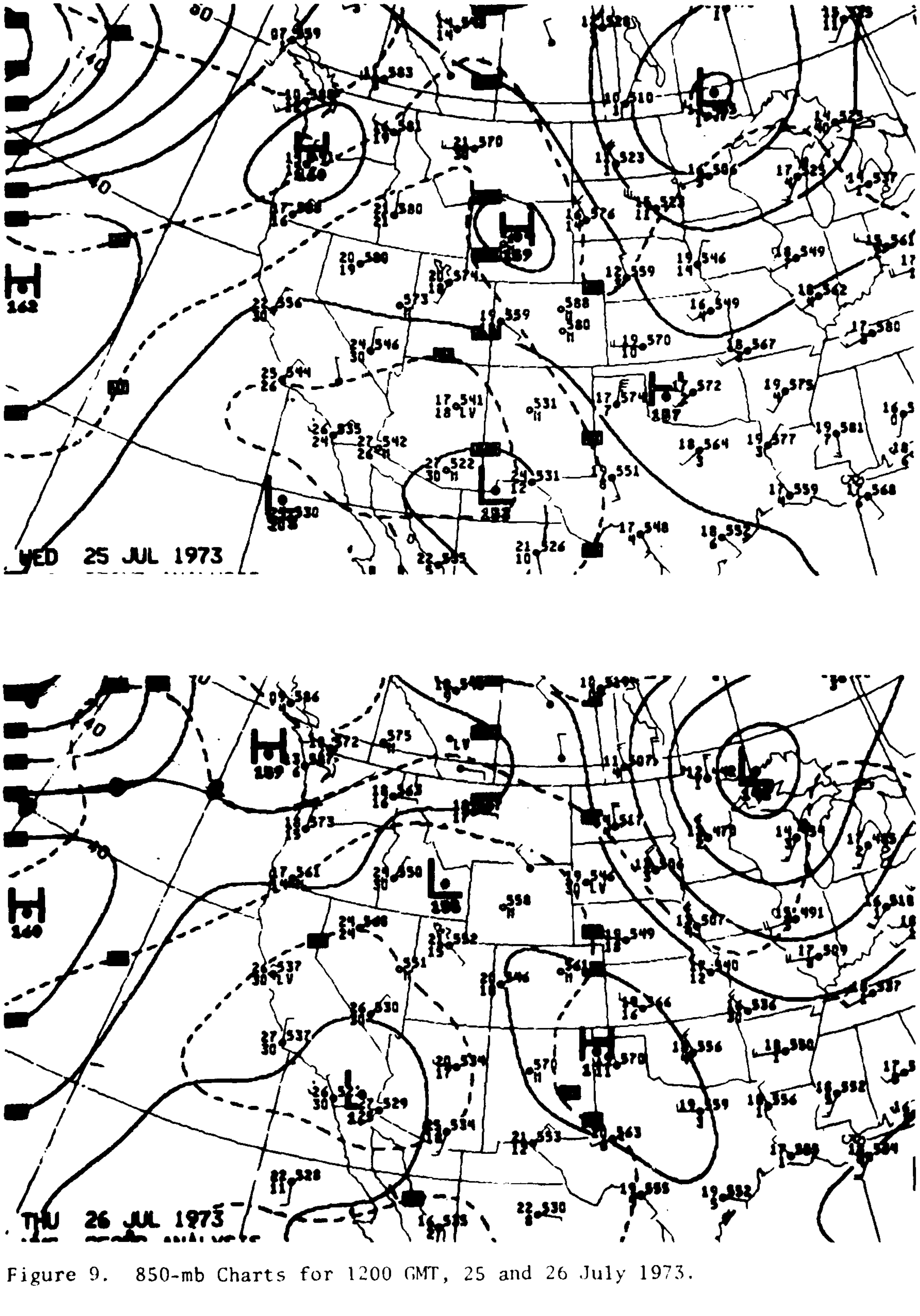


Figure 9. 850-mb Charts for 1200 GMT, 25 and 26 July 1973.

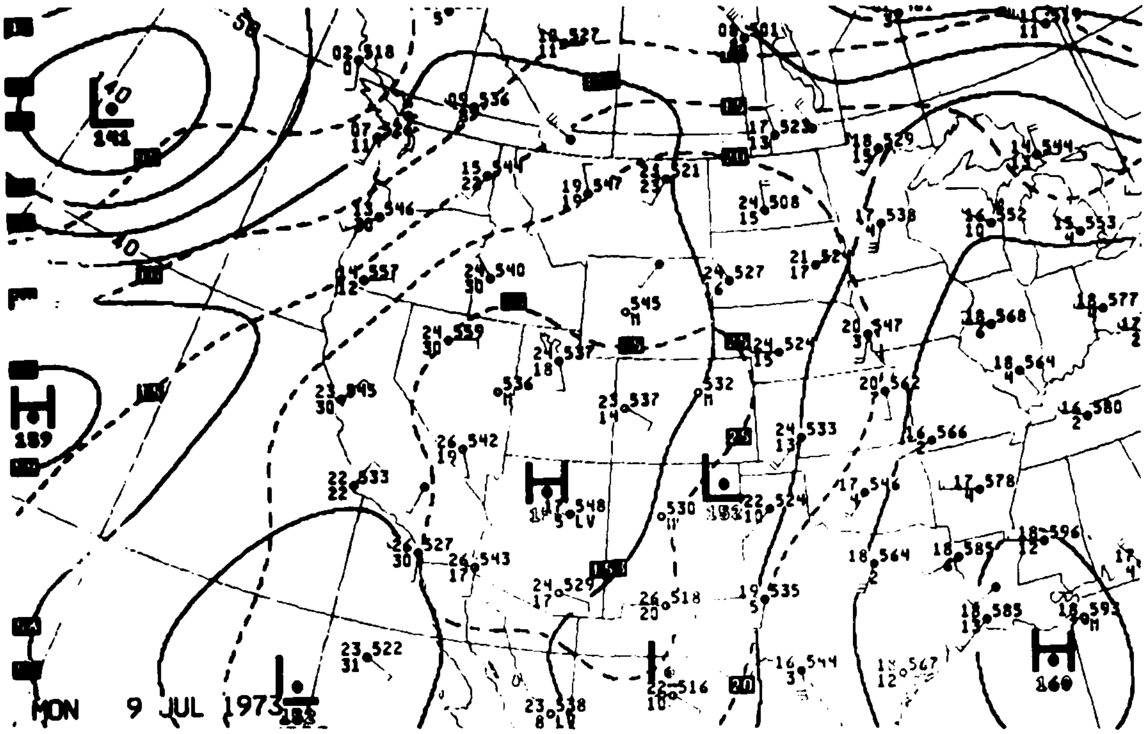
on either day although it was observed in the bay onboard the Acania. For the September 1974 fog cases, visibility degraded at MTY as light westerly winds set in in the late morning hours. Another apparent case of coastal radiation fog occurred on 9 October 1976. On that morning, the inversion at Oakland was at the surface. MTY reported a 7 mi visibility with calm winds until 05 PST when a light westerly wind occurred and the visibility dropped to 1/4 mi.

The preceeding section has dealt with the inversion at low levels or at the ground due to easterly flow from a large-scale high pressure ridge which builds over the Oregon-Washington area. Easterly flow from smaller scale systems concentrated in the surface to 1500 m layer can also produce low inversions and fog. These situations are discussed in the text which follows.

Low Inversion, Small-Scale Synoptic Systems

On 10-11 July 1973, Calspan personnel were aboard the Acania in San Luis Obispo Bay and experienced fog at 08 GMT on the 10th and again at 05 GMT on the 11th. 850-mb charts for 12 GMT on 9 and 10 July are shown in Figure 10. On the 9th, the easterly flow was due to a combination of the sprawling low pressure located southwest of California and a weak high pressure ridge extending across Oregon. By 1200 GMT on the 10th, the easterly flow at Vandenberg was due entirely to the low pressure cell, since the ridge had weakened as low pressure moved in over Vancouver. The inversion was low early on the 10th, with OAK showing a height of 50 m and a sounding from the Acania showing a height of 125 m.

Fog was observed at both Monterey and Vandenberg on the 10th. At Monterey, the fog lasted for 6 hours with a minimum visibility of 1/16 mi. The wind during this period was light westerly. At Vandenberg, visibility was less than 1 mile and lasted 14 hours with a minimum visibility of 1/16 mi; winds were light northwesterly throughout the period. Fog characteristics were representative of fog behavior during low inversion conditions, but in this case, the low inversion came about from a small-scale low-pressure system



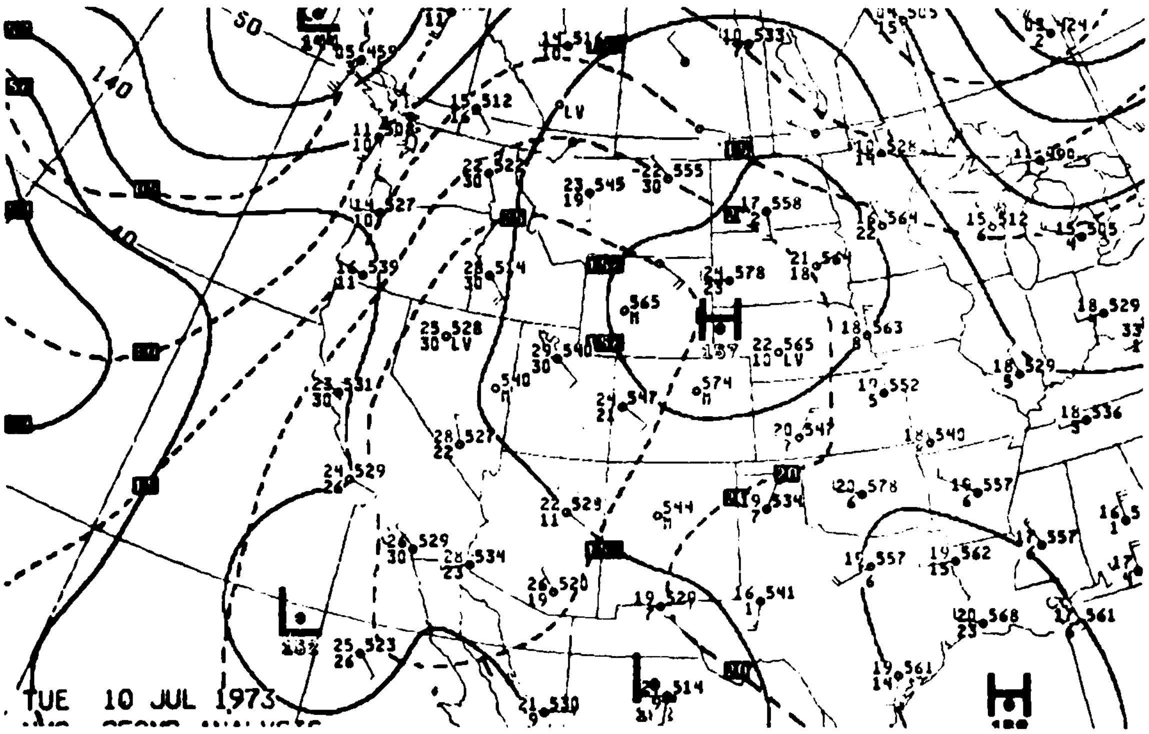


Figure 10. 850-mb Charts for 1200 GMT, 9 and 10 July 1973.

rather than large-scale high-pressure ridge. The driving force on the inversion height in each case was the easterly flow in the low levels and resulting downslope motion.

Small-Scale Low -- 200-300 m Inversion

Previously, we have been discussing low inversion heights, surface-to-100 m, as they are produced by easterly winds and downslope motion from a synoptic scale high pressure ridge and small scale low pressure to the south of such a ridge. Fog also occurs from the stratus lowering process when the inversion is below 400 m but not near the ground. We shall now examine synoptic situations accompanying these inversion heights.

As mentioned in Section 3.1, the inversion lowered to 200 m on 28 July 1972 at both VAN and OAK. The 850 mb chart (Figure 5c) shows a low south of VAN which produced northeasterly flow at VAN. The flow at OAK was light and variable through the lower levels, which along with the 850 mb pattern suggests a mesoscale high in the OAK area. At VAN, the inversion was lowered from the downslope motion counteracting the upward motion of the low, the net result being an inversion height at 200 m. At OAK, the inversion was lowered by the dynamic vertical motion from the mesoscale high alone and thus came down only to 200 m.

Fog was intense during this period, with VAN experiencing about 8 hours with visibility below 1 mi on 27-29 July. Farther north along the coast at MTY, the visibility was below 1 mile on 27-28 July for the same length of time. On 29-30 July, the low moved to north of OAK, putting OAK under the influence of the mesoscale low and VAN under the influence of a mesoscale high. Consequently, the inversion was higher at OAK (above 400 m) than at VAN. With MTY's inversion behaving similar to OAK, the visibility rose to progressively higher values and reached 5 mi with the inversion near 600 m. The inversion at VAN stayed at 300 m and the visibility remained below 1 mi.

Small-Scale Ridge -- Inversion at $\sim$200 m

The time series of inversion height at OAK for the period 28 August-1 September 1972 is shown in Figure 11a. On the 28th, the inversion was at 600 m as the region was under the influence of a small-scale low located off the coast. On the 29th and 30th, a small-scale high pressure ridge was present over the area located between OAK and VAN (Figure 11b), and the inversion lowered to 100 m.

At 00 GMT on both 30 and 31 August, the Acania, located at the Farallon Islands approximately 20 nmi west of San Francisco, experienced stratus lowering fog at about 0300 GMT on both days (see Reference 1). MTY also had fog during this period. The lowest visibility observed in the vicinity of the Farallons occurred at the time of the lowest inversion height at OAK. Visibility subsequently improved as the inversion returned to higher heights.

Synoptic Scale Ridge -- Northeasterly Wind Oscillation

On 23-25 August 1974, the Acania performed a series of east-west tracks to about 50 nmi from Arcata, CA (see Reference 3). Three such tracks were:

Time	Weather
12 GMT 23rd to 00 GMT 24th	Fog
00 GMT 24th to 12 GMT 24th	Stratus Only
12 GMT 24th to 00 GMT 25th	Fog

Figure 12 shows the 850 mb charts at 12 hour intervals starting with 12 GMT on the 23rd. The data suggest northeasterly flow and downslope motion at both 12 GMT times and north-northwesterly at 00 GMT on the 24th west of Arcata. The occurrence of fog, as opposed to stratus in those offshore waters, appears to have been related to inversion height movement above and below the critical 400 m level as the flow shifted away from and then back to the northeasterly sector.

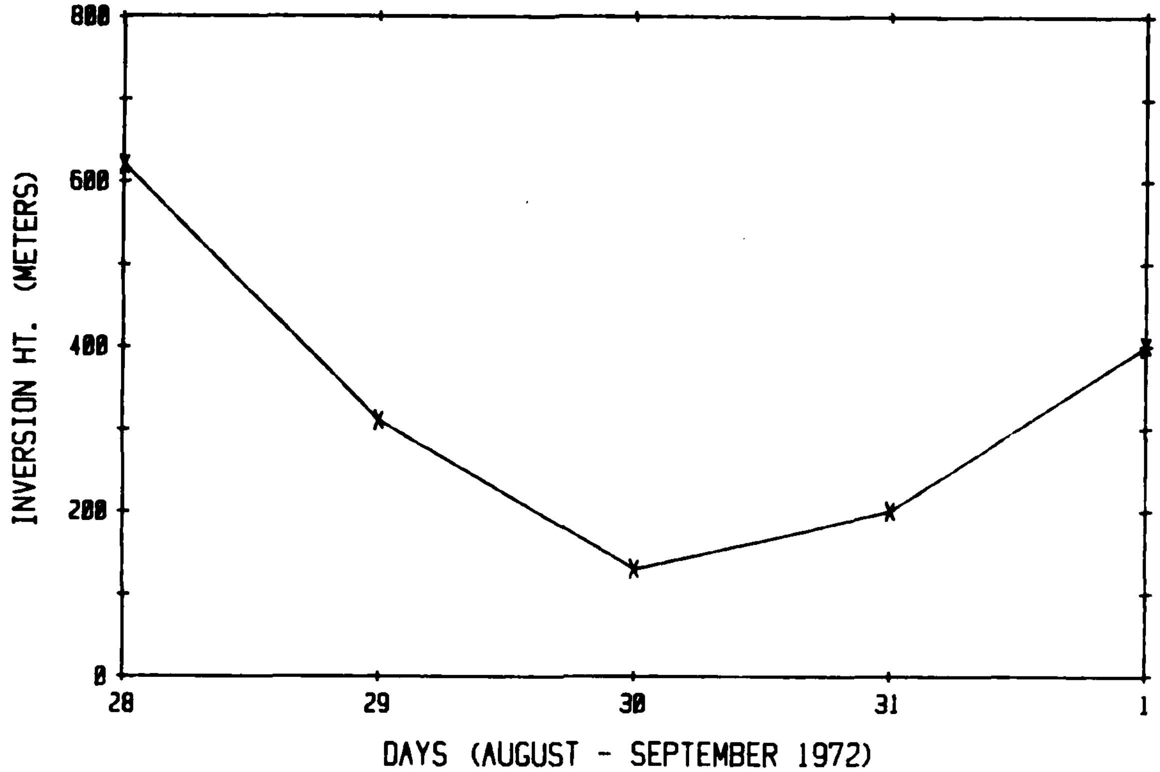


Figure 11a. Inversion Height Time Series for Oakland,CA, 28 August - 1 September 1972.

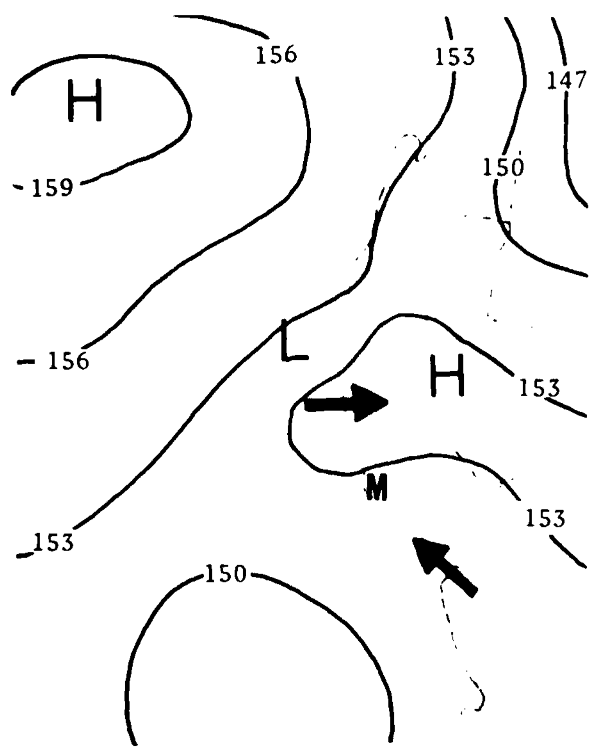


Figure 11b. 850-mb Chart for 1200 GMT, 30 August 1974.

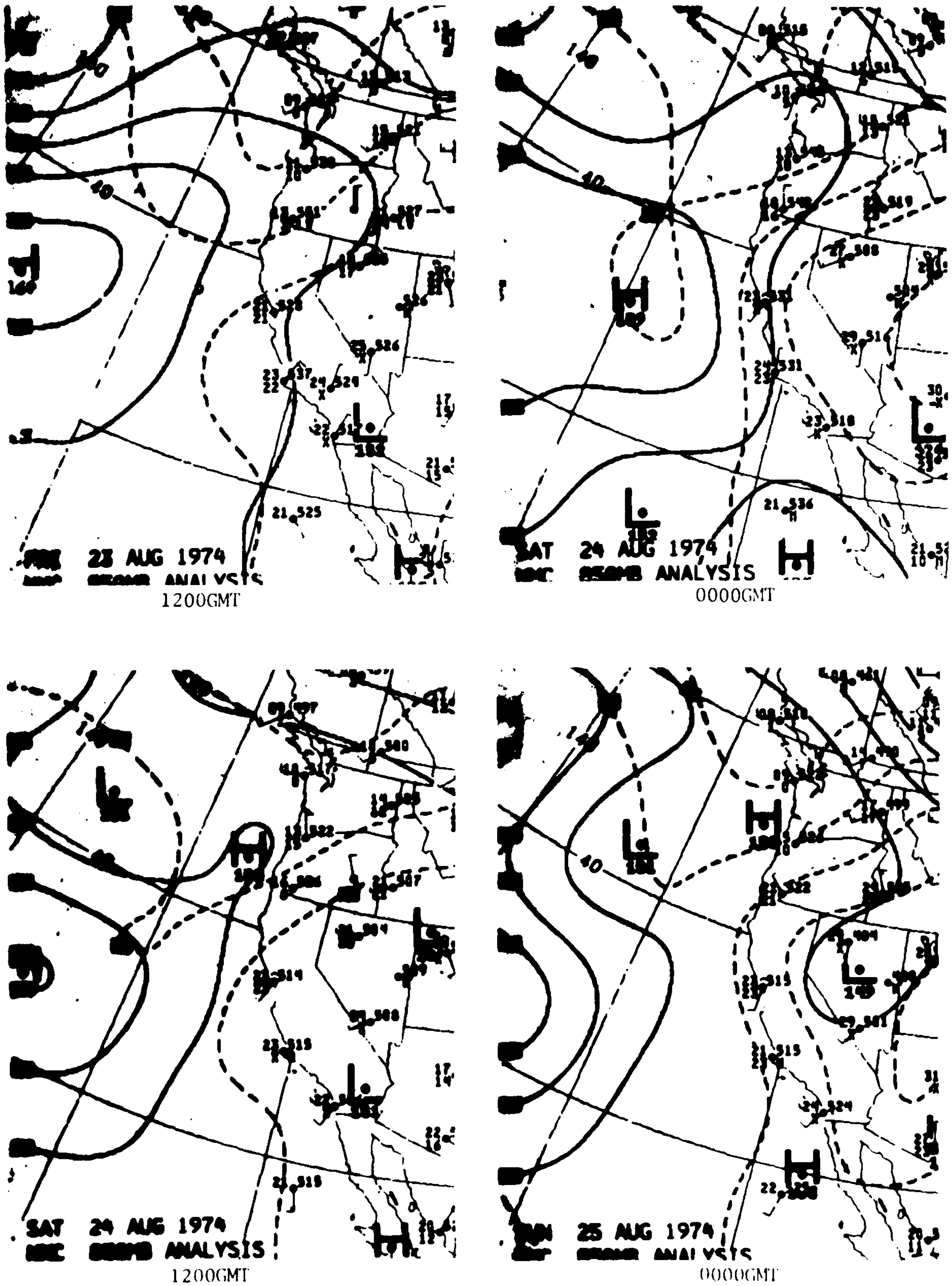


Figure 12. 850-mb Charts for 1200 GMT, 23 August 1974 to 0000 GMT, 25 August 1974.

Stratus Lowering -- Inversion Fluctuating Around [illegible]

The Acania was cruising northwestward [illegible] of 13 October 1976 homeward bound at the [illegible] when fog was encountered just west of Catalina [illegible]. [illegible] persisted until the Acania reached the seaward [illegible] at 2200 GMT.

The inversion height time series [illegible] at San Diego is shown in Figure 13. The [illegible] 12th, dipped to 300 m on the 13th and then [illegible]. The fog occurred during the time period when the [illegible]. The inversion dipped below 400 m on the 13th [illegible] turned winds to easterly at San Diego which was [illegible] to south and the ridge to the north. This situation [illegible] pressure inversion height being depressed by downslope motion. The resulting inversion height was thus not at high levels but at a depressed level below the normal level associated with the larger scale synoptic pressure pattern.

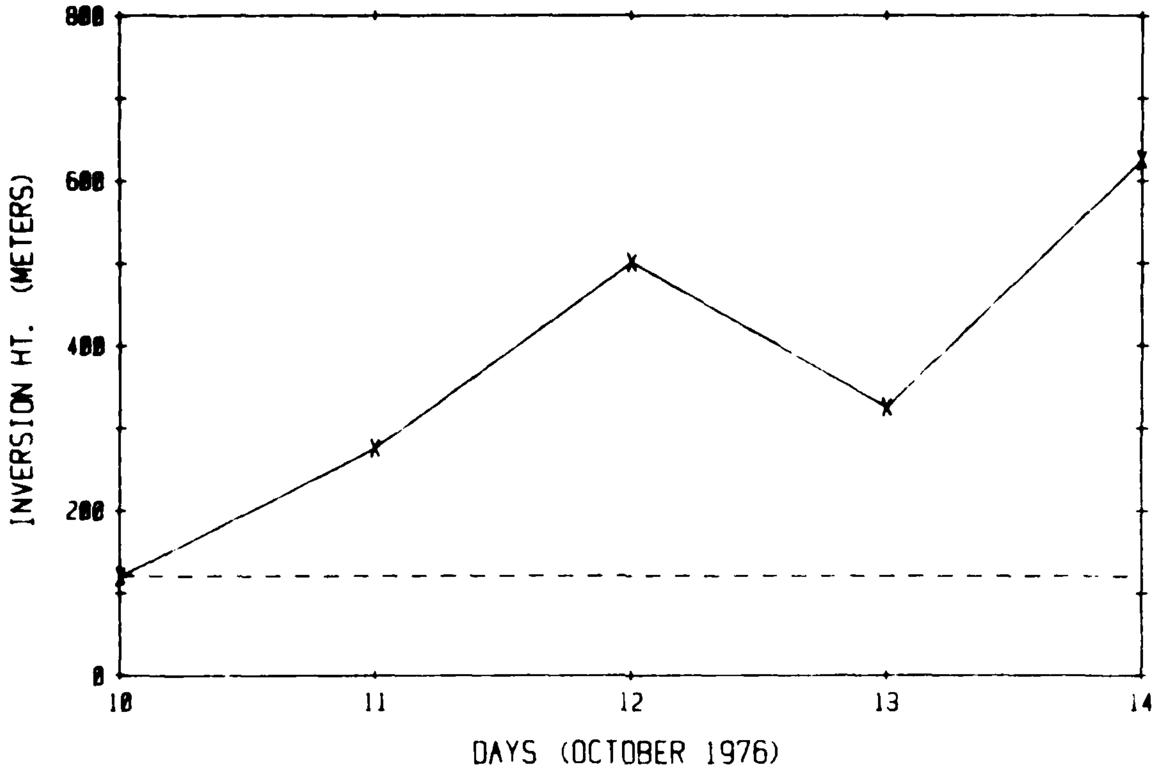


Figure 13a. Inversion Height Time Series for San Diego,CA, 10-14 October 1976.

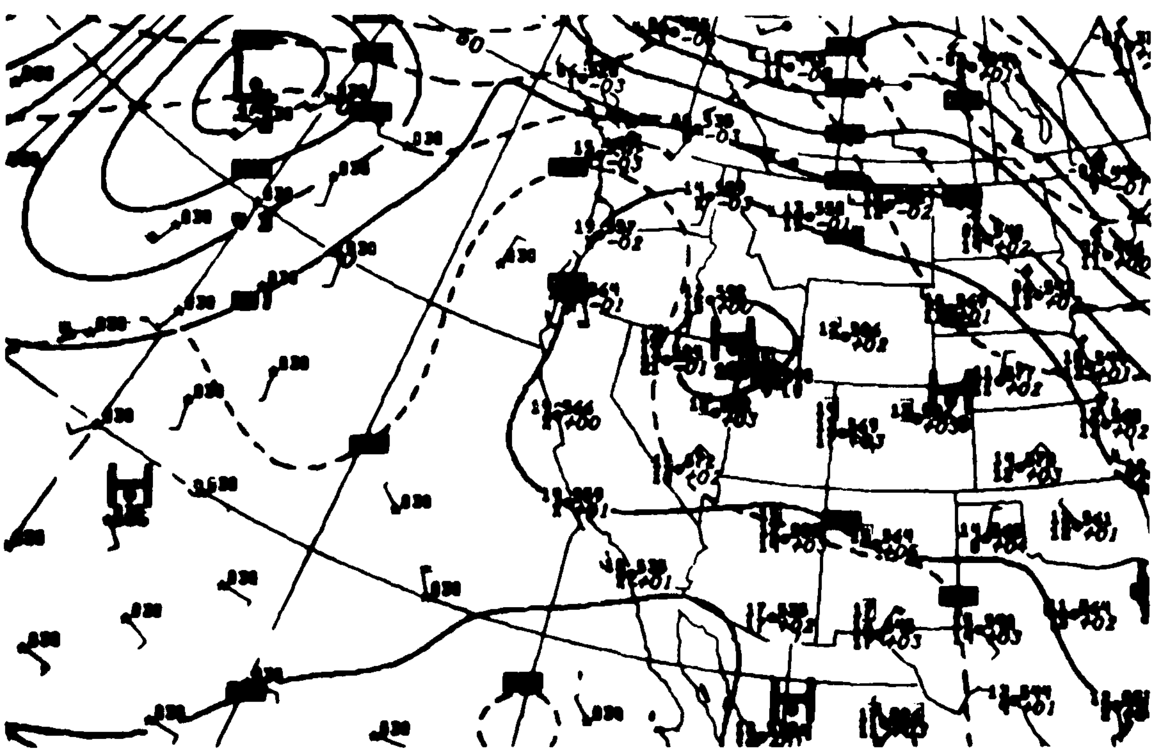


Figure 13b. 850-mb Chart for 1200 GMT, 13 October 1976.

Section 4

FOG CHARACTERISTICS IN THE NORTHERN GULF OF MEXICO

Under previous NASC Contract (No. N00019-79-C-0186), Calspan in collaboration with the Naval Avionics Center (NAC), the Naval Coastal Systems Center (NCSC) and the Coastal Studies Institute (CSI), participated in a study aboard NCSC's offshore platform, STAGE I, to obtain data describing marine fogs and marine boundary layer characteristics in the northern Gulf of Mexico. As depicted in Figure 14, Stage I is located ∿20 km southwest of Panama City, Florida. The field effort, dubbed Panama City II, was conducted during a four-week period in November-December 1978. Aerosol and meteorological data obtained during Panama City II were reduced and provided in a "data volume" (Ref. 13) under Contract N00163-79-C-0049 from NAC, and aerosol data were summarized in a formal paper (Ref. 16). Fog data could not be analyzed within the scope of those previous contracts.

Analysis and interpretation of data describing specific fog characteristics and the circumstances of some of the fog occurrences observed during the Panama City II field effort are presented in this Section. A summary of the general circumstances and characteristics of the fogs observed during the field study may be found in Section 4.1. Specific analyses of the fogs of 9-10, 2, and 8 December 1978 are presented in Sections 4.2, 4.3 and 4.4, respectively. Visibility records for all fogs, except those of 9-10, 2, and 8 December, are provided in Appendix B.

Instrumentation Setup

Calspan instrumentation installed on Stage I is listed in Table 4. All recorders, a 'clear-air' visibility monitor, and aerosol sampling apparatus, were housed in the equipment lab, approximately 18 meters above the sea surface. Lo-vol aerosol sampling was accomplished on the main deck, 16 m above the surface. Temperature instrumentation was located at 3 levels (24.7, 9.3, 4.4 m), and a fourth sensor was specially adapted to measure sea surface temperature.

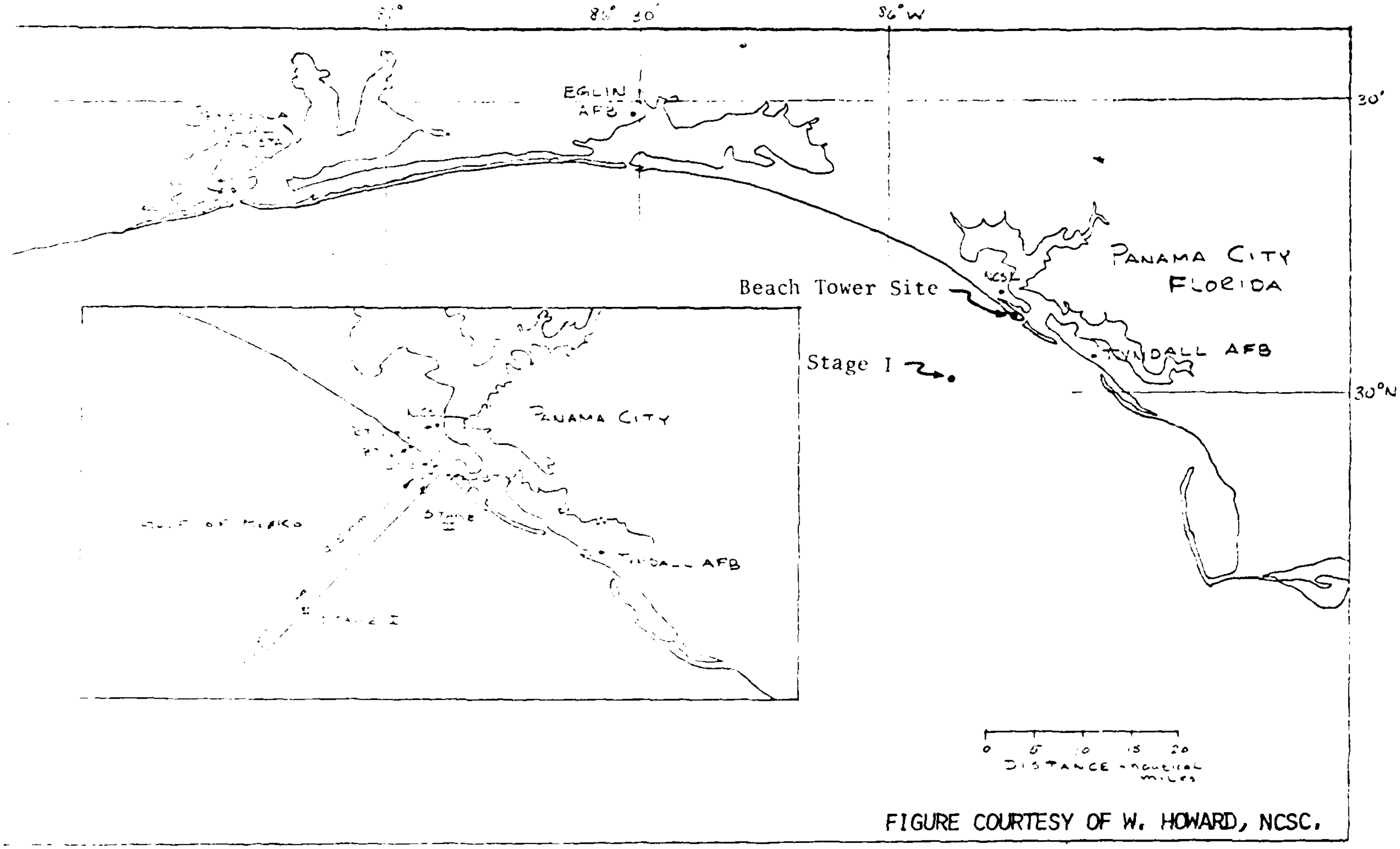


FIGURE 14: CHART OF THE PANAMA CITY AREA SHOWING LOCATION OF NCSC OFFSHORE PLATFORMS

Table 4: CALSPAN INSTRUMENTATION UTILIZED ABOARD NCSC'S STAGE 1, NOVEMBER-DECEMBER 1978

Instrument	Parameter	Height Above Sea Surface
Thermo-Systems Electrical Aerosol Analyzer Mod. 3030	Aerosol size dist. (.01-.75 μm)	18.0 m
Royco Model 225 Particle Counter	Aerosol size dist. (.3-5. μm)	18.0 m
Calspan Sea Spray Sampler (gelatin repl.) (3)	Aqueous aerosol spectra (3.-100 μm)	1-24.0 m
Gardner Small Particle Detector	Total aerosol conc. (>.0025 μm)	18.0 m
Thermo-Sys. Electrostatic Aerosol Sampler, Mod. 3100	Aerosol chemistry by size (>.02 μm)	18.0 m
Casella-Type Cascade Impactor (2)	Aerosol Chemistry by Size (>0.5 μm)	3.0, 16.0 m
Hi-Vol and Lo-Vol Filter Samplers (2)	Bulk aerosol chemistry	3.0, 16.0 m
Calspan Thermal Diffusion Chamber	CCN activity spectra (0.2-2.0% S)	18.0 m
Calspan Fog Droplet Sampler (gelatin repl.)	Fog drop size dist. (3.-100. μm)	1-24.0 m
Calspan Fog Water Collector (impaction)	Fog water chemistry	20.0 m
EG&G Forward Scatter Meter,* Mod. 107 (2)	Visibility (60-6000 m)	4.0, 25.0 m
MRI Integrating Nephelometer, Mod. 2050	Scattering Coeff. (.1-100x$10^{-4}m^{-1}$) Visibility (5-80 km)	18.0 m
Foxboro Temperature System (4 sensors)	Sea surface and air temperature	sea surface, 4.4, 9.3, 24.2 m
Gill Anemometers (2)	Vertical Wind	4.4, 24.7 m
Foxboro Dew Point System (2 sensors)	Dew point temperature	4.4, 24.2 m
Hg Thermometers	Wet/Dry bulb temperatures	17.0 m
Beckman-Whitley Wind System*	Wind speed and direction	24.7 m
Wave Staff (NCSC probe)	Wave Height	sea surface

*A Forward Scatter Meter and a Skyvane Wind System were also located at a beach site ~150 m inland and 6 m above the ground surface.

Dewpoint sensors were installed at the 24.7 and 4.4 m heights, and a sling psychrometer was utilized at deck level (17 m). Horizontal (24.7 m) and vertical wind (24.7 and 4.4 m) instruments were located away from the platform on booms (on the south corner) to minimize effects of the platform on the measurements. Fog visibility monitors (one owned by NCSC) were located at the 24.7 m and 4.5 m heights, and fog droplet and sea spray samplers (for size spectra data) were located at 3 heights above the surface: 23.5 m, 16.5, and at a low level where an elevator platform allowed for data collection from 0.5 m to 4.5 m above the sea surface. All semipermanently installed instruments were located on either the south corner or southwest side of the Stage; lo-vol aerosol and droplet samplers were moved, as required, to the upwind side to account for changes in wind direction. Data were acquired continuously with this instrumentation during the period $\sim$17 November through 12 December 1978.

In addition to the instruments housed on the platform, a fog visibility monitor and horizontal wind instrumentation were located at a shoreline site (NCSC Beachtower #4) near the entrance to St. Andrews Bay. The NCSC-owned visibility device was set up and calibrated by Calspan personnel in late October, prior to the field effort. Calspan wind instrumentation was installed at the Beachtower and calibrated on 15 November.

4.1 Summary of Fog Circumstances and Characteristics

During the period 15 November-12 December 1978, a total of 6 fog situations, in which visibility degraded to $\leq$6000 m, occurred at the offshore platform, Stage I; in 3 of those fogs, surface-level visibility dropped below 1000 m. (A total of approximately 40 hours of fog data, including $\sim$100 droplet samples, was logged at the platform.) Visibility data at the shoreline site are available for the period 1 November-12 December, and, for that period, a total of 12 fogs occurred at that site, 8 of which occurred during the period 15 November to 12 December. Of the fogs observed during the period 15 November-12 December, 2 occurred offshore at the Stage but not at the Beach site and 4 occurred at the Beach Site but not at Stage I; 4 fog episodes occurred concurrently at both the coastline and offshore sites.

Occurrence and meteorological data for the fogs encountered during the Panama City II experiment are summarized in Table 5. Approximately 36% of the observed fogs occurred with winds of <5 m sec^{-1} from the southeast quadrant; ∿43% of the fogs occurred with winds of <5 m sec^{-1} from the northeast quadrant; one fog, each, occurred under SW-wind, NW-wind and calm conditions, respectively. At the Beach Site, average duration of the fogs (for visibility <6000 m) was 4.7 hr. Of the 12 fogs observed at the Beach Site, 60% had minimum visibilities lower than 1000 m; and the <1000 m visibility condition persisted for an average of 2.3 hr. For fogs in the visibility category >1000 m, minimum visibility was typically ∿1600 m. When visibility dropped below 1000 m at the coast, minimum visibilities were generally <200 m. For fogs which occurred at both the Beach and Platform sites, fog duration was usually greater and visibility was lower at the coastal site than at the offshore site.

Microphysics data obtained in four of the fogs observed from aboard Stage I are summarized in Table 6. Approximately 70 droplet samples were analyzed to provide this summary. The drop samples were taken throughout the life-cycles of the respective fogs and do not represent dense nor necessarily mean conditions. With this caveat, averaged data from the 17 m level are compared with fog data obtained elsewhere by Calspan in Table 7. It is seen from this presentation that the fogs observed at the offshore platform in the Gulf exhibited smaller drop sizes, lower drop concentrations and substantially smaller liquid water contents than have been measured elsewhere in marine environs. Further, drizzle, which frequently accompanies marine fogs, was not observed in fogs at Panama City.

The foregoing summary indicates that a minimum of ∿85% of the fogs observed during the Panama City II experiment formed as a result of continental/land influences rather than sea surface temperature gradients or discontinuities. (Analyses of wind (Ref. 13) and aerosol (Ref. 16 and 17) data show that Stage I was under the influence of continental air for a minimum of 72% of the time during the experiment.) Evidently, for these land-mass induced fogs, the

Table 5. Fog Occurrences Observed in the Coastal Northern Gulf of Mexico During November-December 1978

	SHORELINE SITE								OFFSHORE PLATFORM SITE					
Date (1978)	ONSET (Time-CST)	END (Time-CST)	Duration (hr)	Min.Vsby. (m)	Time of Min.Vsby. (CST)	Duration of Vsby. <1000m (hr)	General Wind Direction and Speed (m/sec)	Rel.Hum. At Stage I At Time of On Shore (%)	ONSET	END	Duration (hr)	Min.Vsby. (m)	Time of Min.Vsby. (CST)	Duration of Vsby. <1000m (hr)
5 Nov	0300	0430	1.5	1600	0319	0	Calm	-	-		-	-	-	-
7 Nov	0830	1315	4.8	740	1115	0.1	SE/2.5-5.0	-	-	-	-		-	-
11 Nov	1310	1445	1.6	85	1420	0.4	NE/<2.5	-			-	-	-	-
14 Nov	0300	1815	5.3	74	0726	1.8	SE/ 5.0	-	-	-		-	-	-
16-17 Nov	2300	0450	5.8	175	0027	2.0	SE/2.5-5.0	-	Did not occur at Stage I			-	-	-
20 Nov	1115	1515	2.0	1250	1240	0	NE/5.0	-	0800	0855	0.9	3100	0820	0
21 Nov	1200	1430	1.5	2030	1125	0	NE/2.5-5.0	62	Did not occur at Stage I					
24 Nov	1115	2130	9.8	1600	1550	0	SW/2.5-5.0	91	1205	2123	9.3	4000	2010	0
27 Nov	1000	1630	6.5	1600	1400	0	NE/2.5	81	Did not occur at Stage I			-	-	-
29 Nov	0310	0450	7.8	250	0643	2.9	NE/2.5-5.0	96	Did not occur at Stage I			-	-	
1 Dec	0630	1030	4.0	80	0633	2.5	NE/<2.5	96	0652	0830	1.5	700	0717	0.4
3 Dec	Did not occur at Beach Site				-	-	SE/2.5-5.0	-	0938	1056	1.3	1300	0940	0
8 Dec	2015	0515	5.0	100	0300	3.1	SE/<2.5	100	0200	0504	3.0	380	0418	1.5
9-10 Dec	Did not occur at Beach Site				-		NW/ 5.0		1610/9th	0830/10th	15.8	200	0500	intermittent

Table 6. Average Fog Microphysics Measured at the Offshore Platform, Stage I, in the Northern Gulf of Mexico, November-December 1978

DATE	5 m Height - MSL						17 m Height - MSL						24 m Height - MSL					
	$\bar{r}$ (μm)	Rad. Size Range (μm)	Conc. (cm^{-3})	LWC (g/m^3)	Vsby (m)	No. of Samples	$\bar{r}$ (μm)	Rad. Size Range (μm)	Conc. (cm^{-3})	LWC (g/m^3)	Vsby (m)	No. of Samples	$\bar{r}$ (μm)	Rad. Size Range (μm)	Conc. (cm^{-3})	LWC (g/m^3)	Vsby (m)	No. of Samples
24 Nov 1978	4.1	1-14	5.0	.002	5500	(15)	4.5	1-14	4.5	.002	5350	(11)	4.2	1-14	5.1	.002	5370	(11)
2 Dec 1978							7.4	2-20	3.4	.009	3330	(10)						
3 Dec 1978							5.0	2-16	3.5	.003	5150	(4)						
8 Dec 1978	9.8	3-24	3.5	.022	2480	(7)	8.5	2-33	6.0	.022	3090	(12)						

Table 7. Average Surface-Level Microphysics for Mature Stages of Dense Fogs Observed by Calspan

		Fog Type	# of Fogs	Mean Rad. (μm)	Typical Drop Size Range (Rad-μm)	Avg. Drop Conc. (cm^{-3})	Avg. LWC ($mg\ m^{-3}$)	Avg. Max. LWC ($mg\ m^{-3}$)	Avg. Min. Vsby. (m)
CONTINENTAL FOGS									
Phillipsburg, PA	Nov 1965	Frontal	(2)	3.9	2-25	-	170	-	100-200
Seattle, WA	Feb 1970	Radiation	(4)	8.8	2-30	23	100	160	200-600
Elmira, NY	Aug 1970	Valley	(7)	9.0	2-28	19	90	150	200-600
Vandenberg AFB, CA	Sep 1971	Coastal Stratus Low.	(3)	8.4	2-100	11	80	120	400-1000
Vandenberg AFB, CA	Jul 1972	Coastal Stratus Low.	(8)*	6.2	2-115	110	220	350	150
Los Angeles, CA	Nov 1971	Radiation	(2)	~1	<2-40	>1000	170	310	40-200
Travis AFB, CA	Jan 1973	Radiation	(13)	6.3	2-15	75	110	180	100
Otis AFB, MA	Sep 1976	Radiation	(1)	7.1	<2-20	78	170	190	60-100
Otis AFB, MA	Sep 1976	Advection (Coastal)	(1)	7.9	2-20	31	90	120	250-300
Otis AFB, MA	Jul 1980	Advection (Coastal)	(4)	7.5	2-22	40	110	150	150-300
MARINE FOGS AT SEA									
West Coast:	Aug 1974	Convergence	(2)	10.0	2-115	20	125	230	100
	'72,'73,'74	Coastal Radiation	(6)	8.5	2-25	45	100	230	100-200
	'72,'74,'76	Stratus Lowering	(4)	8.0	2-115	10	30	70	300-1000
	'74 & '76	Shallow Patches		5.6	2-20	25	60	130	200-300
	Sep 1976	Frontal	(1)	8.5	2-25	17	60	95	200-600
Nova Scotia:	Aug 1975	Shallow Cold Water Adv.	(1)	5.2	2-15	45	30	150	100
		Deep, Dense Advection	(6)	7.5	2-115	75	230	320	80-150
		Deep, Moderate Adv.	(4)	5.6	2-115	45	55	85	200-600
North Gulf of Mex:	Nov-Dec '78		(4)*	6.4	2-30	5	10	40	200-700

*Data obtained at 15 m height above surface.

relatively warm waters of the coastal Gulf play a role in eroding (by causing evaporation of fog) their near-surface characteristics. This influence is reflected in the shorter durations and higher visibilities measured at the platform (compared to the Beach site) and the lower than average (for marine fog) liquid water contents observed in the near-surface levels of these fogs over the water. Such higher visibilities and low water contents are probably not typical of surface-level conditions for Gulf fogs formed in other than coastal regions of the Gulf, especially in the outflow region of the Mississippi and other major rivers.

4.2 The Sea Smoke of 9 and 10 December 1978

Sea smoke forms when very cold air moves over warm water. It is characterized by streamers of visible fog which rise from near the surface and dissipate as they mix with the relatively dry air aloft.

A dramatic episode of sea smoke occurred at Stage I following the cold air outbreak on 9 December 1978. Very briefly, a strong cold front passed through the Panama City area at approximately 0700 CST on 9 December. Air temperatures dropped from ~23°C ahead of the front to ~4-6°C approximately 150-300 km behind the front. The axis of the 500 mb trough associated with this surface front extended from a closed low over James Bay to central Texas. By 0600 CST on 10 December, the 500 mb flow was zonal, and the surface front was located ~800 km east of the Stage, putting Stage I well into the cold northerly flow behind the front. Minimum air temperatures of ~1.0°C for this cold air outbreak were recorded on Stage I at 0700 on 10 December.

Temperature and dewpoint data obtained on 9 and 10 December are shown in Figure 15. Visibility data from 1600 on 9 December to 1000 on the 10th are shown in Figure 16. Initial indications of a visibility degradation at the 4.5 m level appeared for a brief period around 1640 on 9 December. Notes taken at the time indicate that the coast was clearly visible from both the 5 and 17 m heights. At about 1845, the visibility degradation at 4.5 m became persistent. At the same time, wave height increased to such an extent (2.2 m) that crests began breaking on the grill of the lower deck structure,

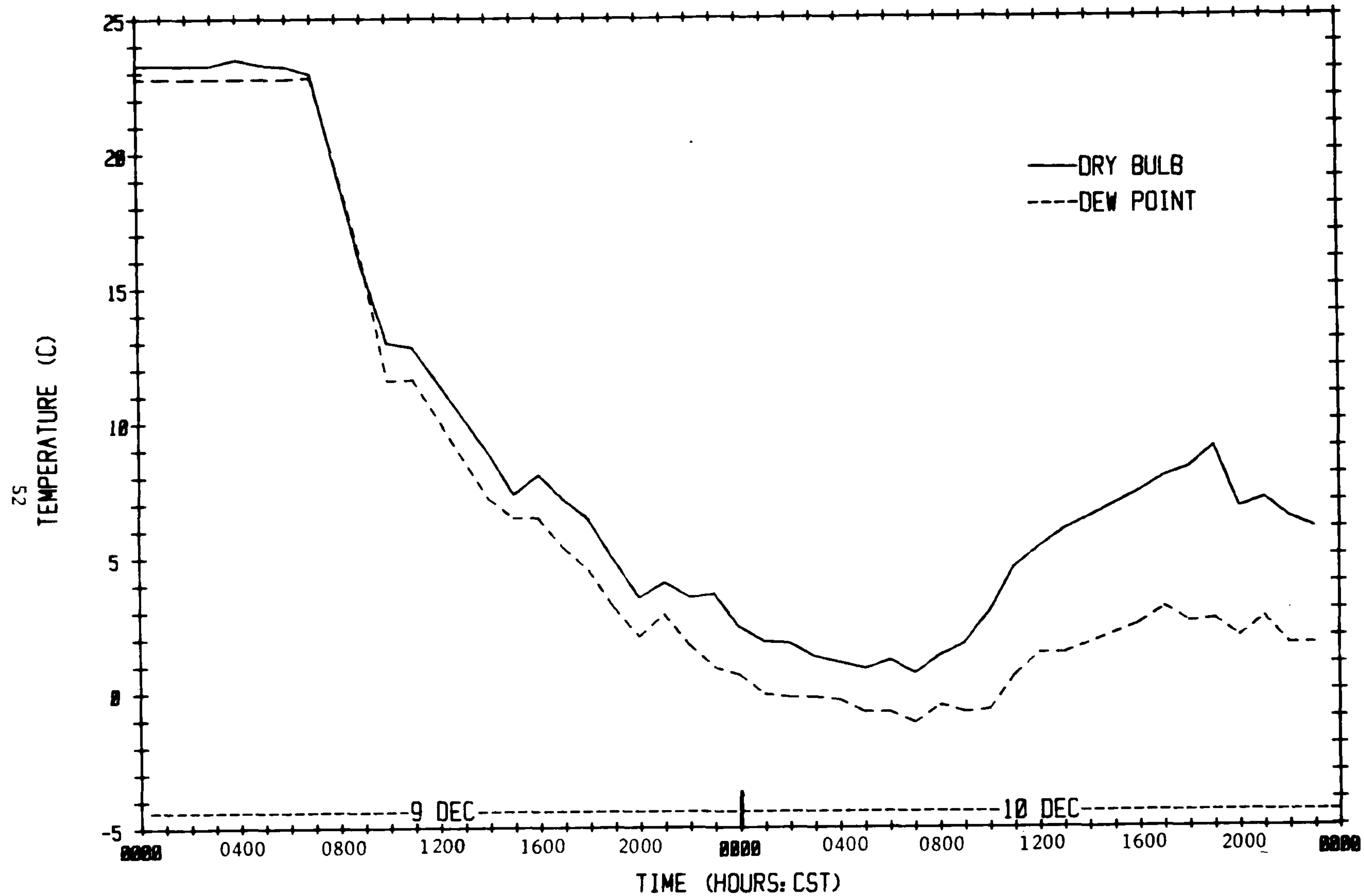


Figure 15. Temperature and Dew Point Data at the 17 m Height on Stage 1 for the Period 0000 CST 9 Dec to 2300 CST 10 Dec 1978.

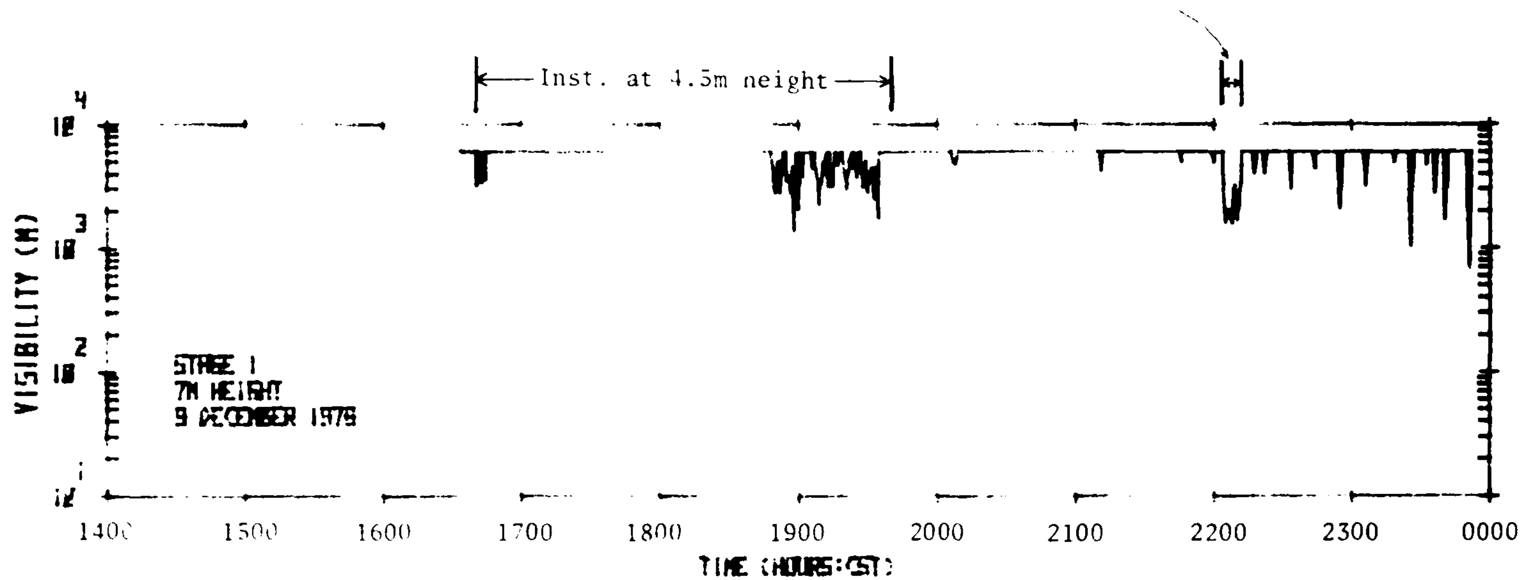


Figure 16. Visibility Record for 9-10 December 1978.

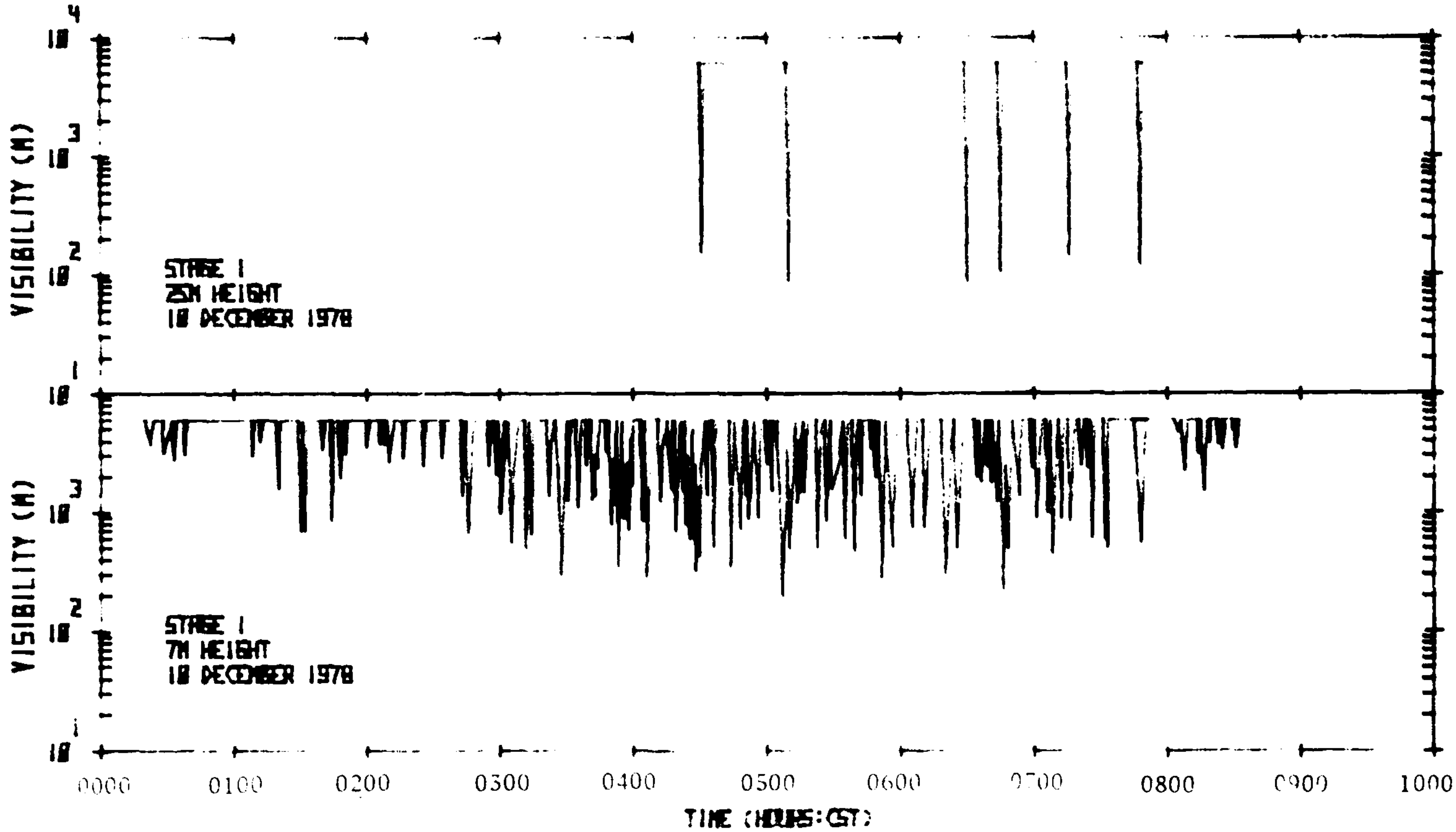


Figure 16. (Cont.)

which led us to believe that the visibility degradation was due to spray. The visiometer was moved to the 7 m height as a protective measure at 1940. Visibility data were obtained thereafter at the 7 m level except for the brief period around 2210, which is noted on the figure. For only a few brief periods during mid-morning on 10 December, fog depth reached 25 m; otherwise fog remained below the 25 m height at the Stage and was nonexistent at the coast.

The analysis presented below is based on the following phenomenological model: As the cold dry air moves over the warm surface water, an extremely unstable low level temperature profile is produced, and extreme mixing occurs. Nevertheless, in a very thin layer immediately above the surface, the air achieves temperature and moisture equilibrium with the water. In the case of sea water, moisture equilibrium occurs at 98% RH, so that condensation does not exist in this thin layer. However, as this thin, warm, near saturated layer of air is mixed with the relatively dry, extremely cold air aloft, the mixing process advanced by Taylor (1917) occurs and is responsible for the formation of the visibile fog.

The data obtained on Stage I relates to this model as follows: The vertical temperature distributions obtained at several pertinent times prior to and during the fog are shown in Figure 17. Considering these distributions and the 10 to 15 m sec^{-1} winds blowing over 1.5 to 2.2 m high waves, it is apparent that mixing was extreme. It is also apparent from the temperature profiles, and indicated schematically by the hatched region of the 0500 profile, that substantial uncertainty exists in the actual temperature distribution at the very low levels. Even worse, considering wave heights of up to 2.2 m, the meaning of numerical values of heights immediately above the surface is highly questionable when based on measurements made at fixed levels on the Stage. Our data, though presented in quantitative terms, must be interpreted with these uncertainties in mind.

In order to apply the mixing theory in examination of the mean temporal and vertical distributions of liquid water, we considered the measured temperature and mixing ratio conditions throughout the fog life cycle in relation to the saturated mixing ratio vs temperature curve as shown in Figure 18. Conditions in the warm, nearly saturated airmass (i.e., that in

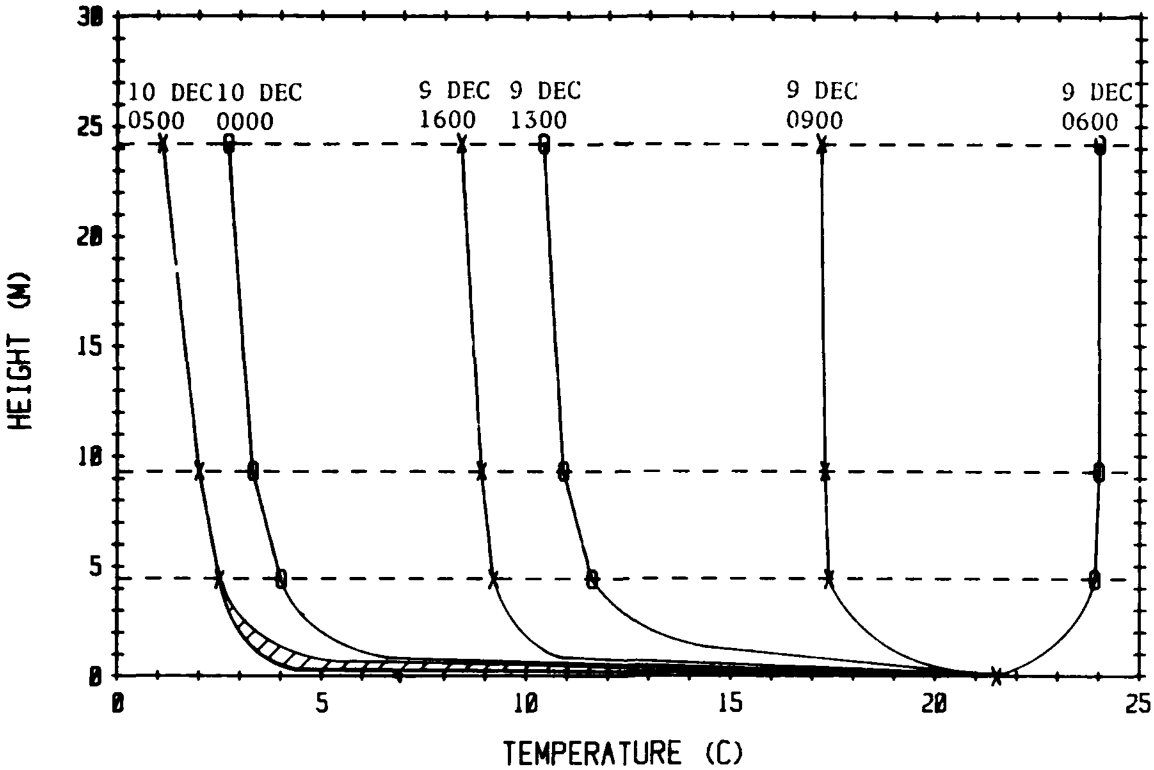


Figure 17. Vertical Temperature Distribution at Stage 1 Prior to and During the Sea Smoke of 9-10 Dec 1978.

the thin layer immediately above the surface) are defined by the sea surface temperature and 98% relative humidity. Conditions in the cold, relatively dry air mass are defined by measurements at the 24.2 m level obtained with the Foxboro temperature sensors and confirmed hourly with manual wet and dry bulb temperature measurements. The conditions at other altitudes for which accurate hygrometric data are not available are defined by observed (or interpolated from Figure 17) temperature at that height and the straight line connecting the two points described earlier. For illustration purposes, examine the straight line characterizing all mixing ratio and temperature conditions from the surface to 24.2 meters at 0500 on 10 December. The mixing ratio is below saturation for all air mass mixtures except those characterized by temperatures between ∿5°C and 20.3°C. From the temperature profile of Figure 17, it is apparent that the 5° mean isotherm existed at some height

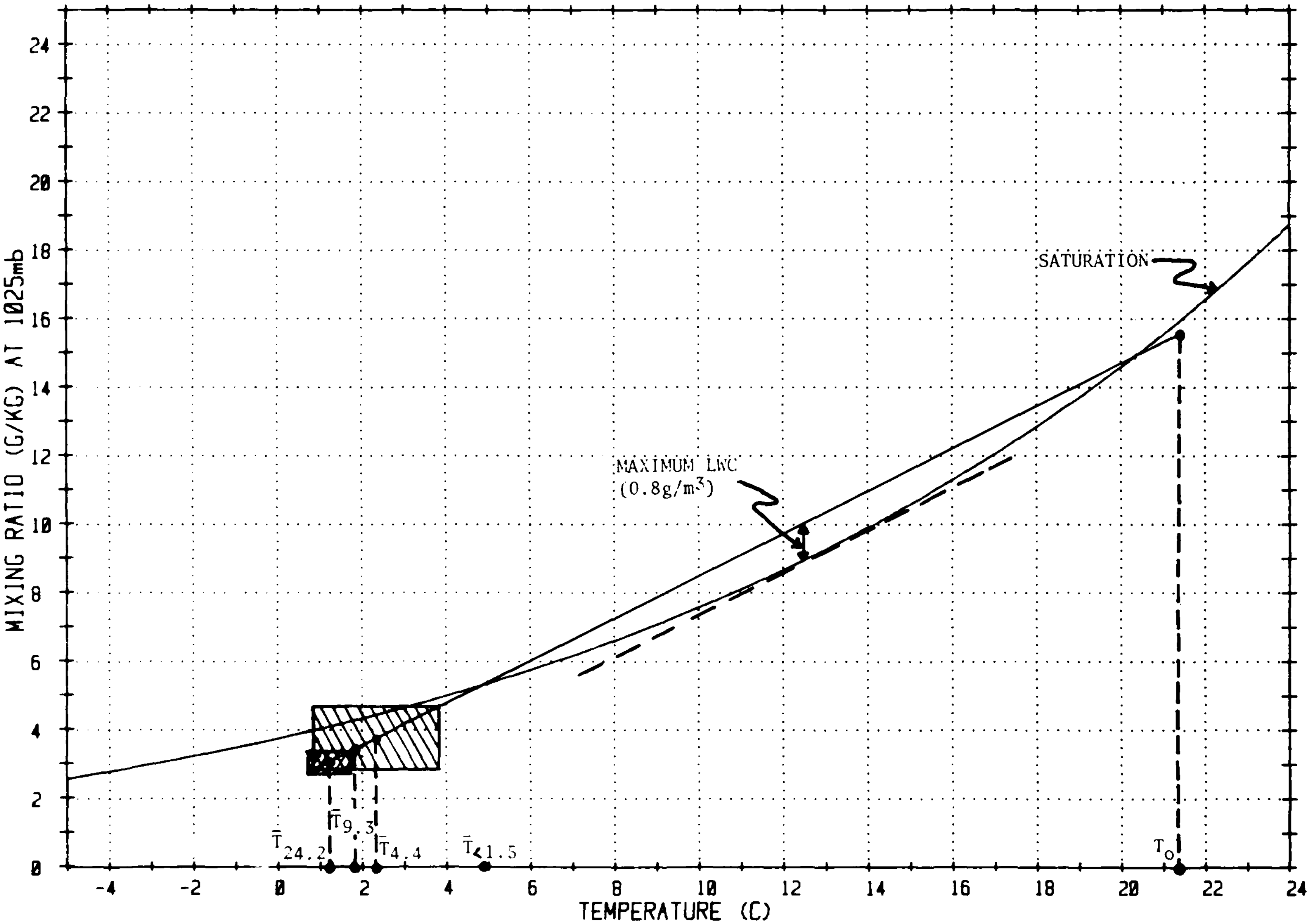


Figure 18. Taylor Mixing Analysis for Mean Conditions at 0500 CST, 10 Dec 1978.

which is below $\sim$1.5 m, which as stated above is not definable with 2.2 m waves. Judging from the rate of change of temperature with height, the height of the mean 20.3°C isotherm must be just centimeters above the surface, but such values are totally meaningless under existing conditions.

The only interpretation that can be made relative to height, therefore, is that the mean thickness of the saturated layer was of the order of a meter and that the mean depth of the unsaturated layer beneath the 20.5° isotherm must have been extremely small, probably on the order of a centimeter. The persistent presence of the visible condensate (i.e., large scattering coefficient) at the 7 m level (see Figure 16) and occasionally at the 24 m level suggests that turbulent eddies carried saturated and near saturated air parcels to heights substantially greater than the mean heights defined by the average temperature and dewpoint data. This hypothesis will be examined later.

From Figure 18 it would appear that the maximum liquid water content was approximately 0.8 g m^{-3} when the mixture was at temperatures between 12° and 13°C. At that time, the Aitken count was 1800 cm^{-3}. To have achieved this liquid water content, these nuclei would have had to grow to a mean volume radius of 10 μm. (Considering the very small average thickness of the saturated layer, it would appear that the rates of change of temperature and mixing ratio at this early stage of mixing were so great that equilibrium was never achieved. Evidence to be presented later will show that very substantial growth must have been achieved.)

Similar analyses for several other interesting times during the fog are shown in Figure 19. The analysis for 1300 on 9 December shows the straight line connecting the two initial air masses (i.e., the surface and 24.2 m air masses) to be very nearly tangent to the saturation mixing ratio curve, indicating that initial condensation occurred at about that time, more than three hours before the first observation of scattering at the 4.5 m level. (We now believe that the scattering observed between 1640 and 1845, which caused us to move the visiometer up to the 7 m level, was sea smoke and not sea spray as thought at the time.) The sequence of analyses (Figure 19) for data obtained on 10 December suggests that condensation continued to occur until approximately 1100, more than two hours after scattering was last detected.

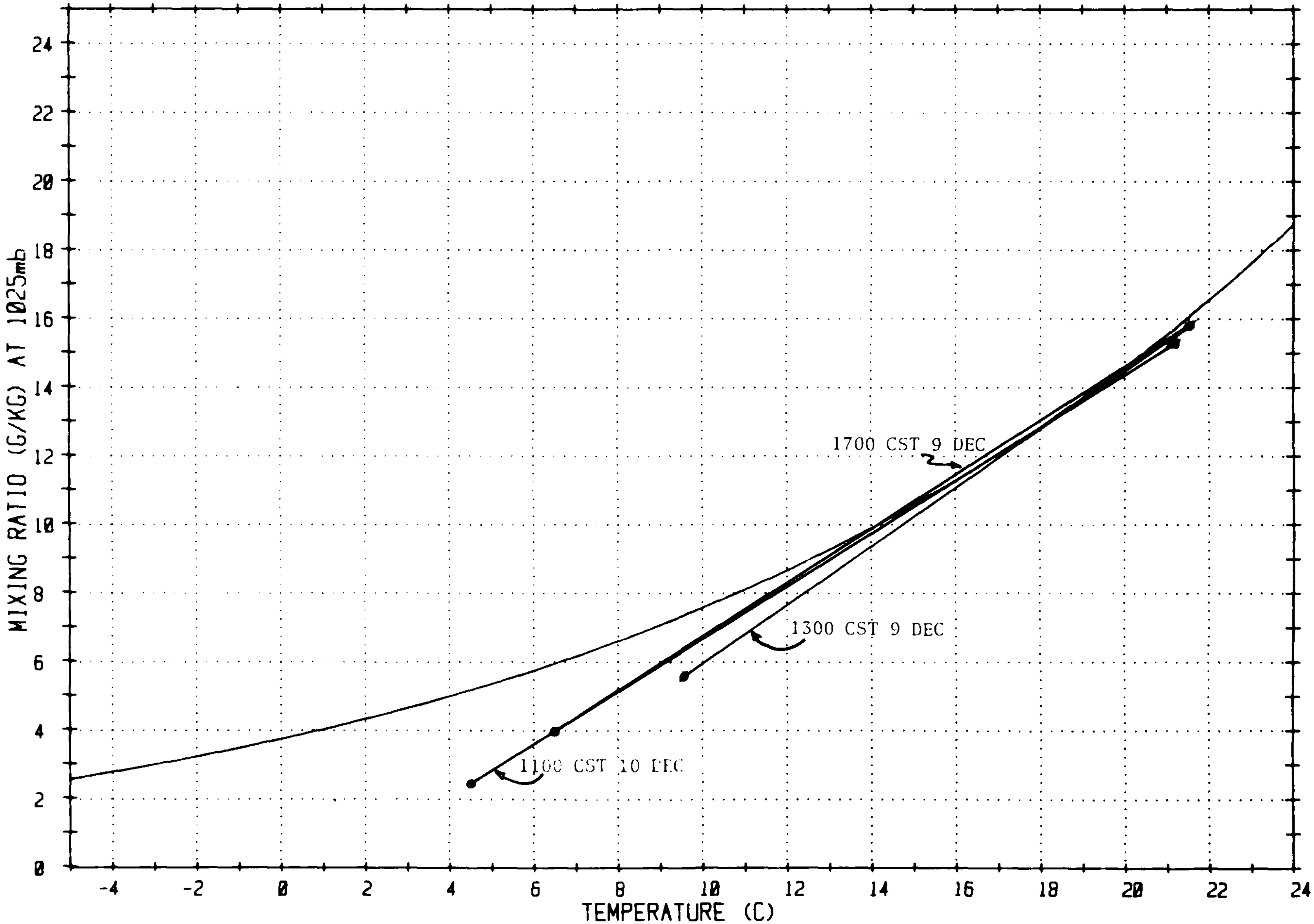


Figure 19. Taylor Mixing Analysis for Other Times During the Sea Smoke of 9-10 Dec 1978.

Analysis of the 1700, 9 December data, just 20 minutes after initial scattering was observed, indicates that maximum LWC between 0.2 and 0.3 g m^{-3} was required at very low levels before even the minimum scattering was observed at the 4.5 m level. These data again suggest that the observed phenomenon was never in an equilibirum condition; further analysis would require consideration of the relatively rapid fluctuations of temperature and humidity.

Examination of the temperature records reveals well correlated cyclic fluctuations at the three levels (24.2, 9.3 and 4.4 m) with recognizable periods ranging from 2 to 5 minutes. Higher frequencies certainly exist, but the data acquisition rate and response time of the Foxboro system are not sufficient to permit quantitative analysis. Peak-to-peak temperature excursions at the three levels were typically 0.5, 1.0 and 1.5°C, respectively, with maximum excursions approximately half again that large at each level. Dew point data obtained at 24.2 m and 4.4 m show similar fluctuations occurring at both levels. Typical dewpoint excursions at both levels are of the order of 1.5°C, with maximum excursions approximately 3°C.

Quantitative analysis of temperature and dewpoint data acquired between 0400 and 0600 on 10 December, the period of maximum fog density, yields the following correlation coefficients:

$$K(\overline{T_{24.2}\ T_{9.3}}) = 0.85$$

$$K(\overline{T_{24.2}\ T_{4.4}}) = 0.7$$

$$K(\overline{T_{9.3}\ T_{4.4}}) = 0.88$$

$$K(\overline{T_{D(24.2)}\ T_{D(4.4)}}) = 0.84$$

These high values show that turbulent eddies which are substantially larger than the 24 m height of the Stage are moving past the tower with the wind. This agrees with the observed periodicity of temperature fluctuations which are of the order of 100 seconds, suggesting that identifiable air parcels are of the order of 500 to 1000 m long. An important secondary conclusion is that the temperature sensors, with response times of approximately 5 seconds, are adequate for following the major temperature fluctuations. With this point established, it is reasonable to proceed with the Taylor mixing analysis based on short time scales.

Our approach to this analysis is illustrated by the cross hatched "boxes" centered on the average values of temperature and dewpoint at the 24.2 and 4.4 m levels in Figure 18. These boxes indicate the extent of "typical" observed fluctuations in temperature and dewpoint at each of these levels during the two-hour period centered on 0500. Comparison of short-term fluctuations of temperature and dewpoint reveal very little correlation (correlation coefficient $\sim$0.2 at each level). We believe that this is due to the slow response of the dewpoint sensor. While logic tells us that the actual instantaneous conditions must have fallen on the straight line shown in Figure 18, the quantitative data suggest that the actual conditions at each measurement height may have been instantaneously anywhere within these boxes.

Let us examine the possibilities under the two extreme sets of assumptions: (1) There was a perfect positive correlation of temperature and dewpoint, and (2) There was a perfect negative correlation of temperature and dewpoint.

1. With a perfect positive correlation of temperature and dewpoint, the atmosphere at all measurement levels would have been unsaturated at all times. Maximum relative humidity would have been 92, 87 and 83%, respectively, at 4.4, 9.3 and 24.2 meter heights.

2. With perfect negative correlation of temperature and dewpoint, which would provide maximum opportunity for supersaturation to exist, the data would indicate that supersaturation never existed at 24.2 meters, existed for about 1% of the time at 9.3 meters and possibly as much as 20% of the time at 4.4 meters.

At this point in the analysis we asked, what fraction of the time was scattering observed at the 7 m level where the EG&G Forward Scatter Meter was located? Careful analysis of the minute by minute data obtained between 0400 and 0600 produced the cumulative distributions of visibility and scattering coefficient which are presented in Figure 20. The scattering coefficient exceeded 8×10^{-4} at that level more than 50% of the time. Substantiating data were obtained from the MRI Nephelometer at the 18 m level which recorded a B_{scat} at 1.1×10^{-4} m^{-1}.

From these analyses, we must conclude that the observed scattering resulted from an aerosol that existed under subsaturated conditions. An examination of the source of this scattering was performed.

Because of aerosol contamination (exhaust from diesel/electric generator) which always accompanied northerly winds on Stage I, we do not have complete aerosol data for computing scattering coefficient. For this specific time interval, we know only that the Aitken count was 1800 cm^{-3}. The initial comparison was made simply by determining the mean volume radius of these 1800 cm^{-3} particles required to produce a scattering coefficient of $10^{-3} m^{-1}$.

$$B_{scat} = 2\pi \bar{r}^2 n = 10^{-3}$$

$$\bar{r}^2 = \frac{10^{-3} m^{-1}}{2\pi \times 1800 \times 10^6 m^{-3}} \approx 10^{-13} m^2$$

$$\bar{r} \approx 0.3 \ \mu m$$

Assuming all nuclei to be sea salt, the mean dry radius would be $\sim$1/2 that at 85% RH, or $\sim$0.15 μm. Nuclei in this size range would activate at approximately 0.02% supersaturation. The CCN activity spectrum obtained in the same air mass at 1852 CST on 9 December indicated 1960, 1610 and 1240 nuclei (cm^{-3}) activated at 1.0, 0.5 and 0.2% supersaturation, respectively. Such salt particles have radii of the order of 10^{-2} μm and smaller. If the particles responsible for scattering are in equilibrium with the ambient atmosphere, a few giant nuclei must then be responsible.

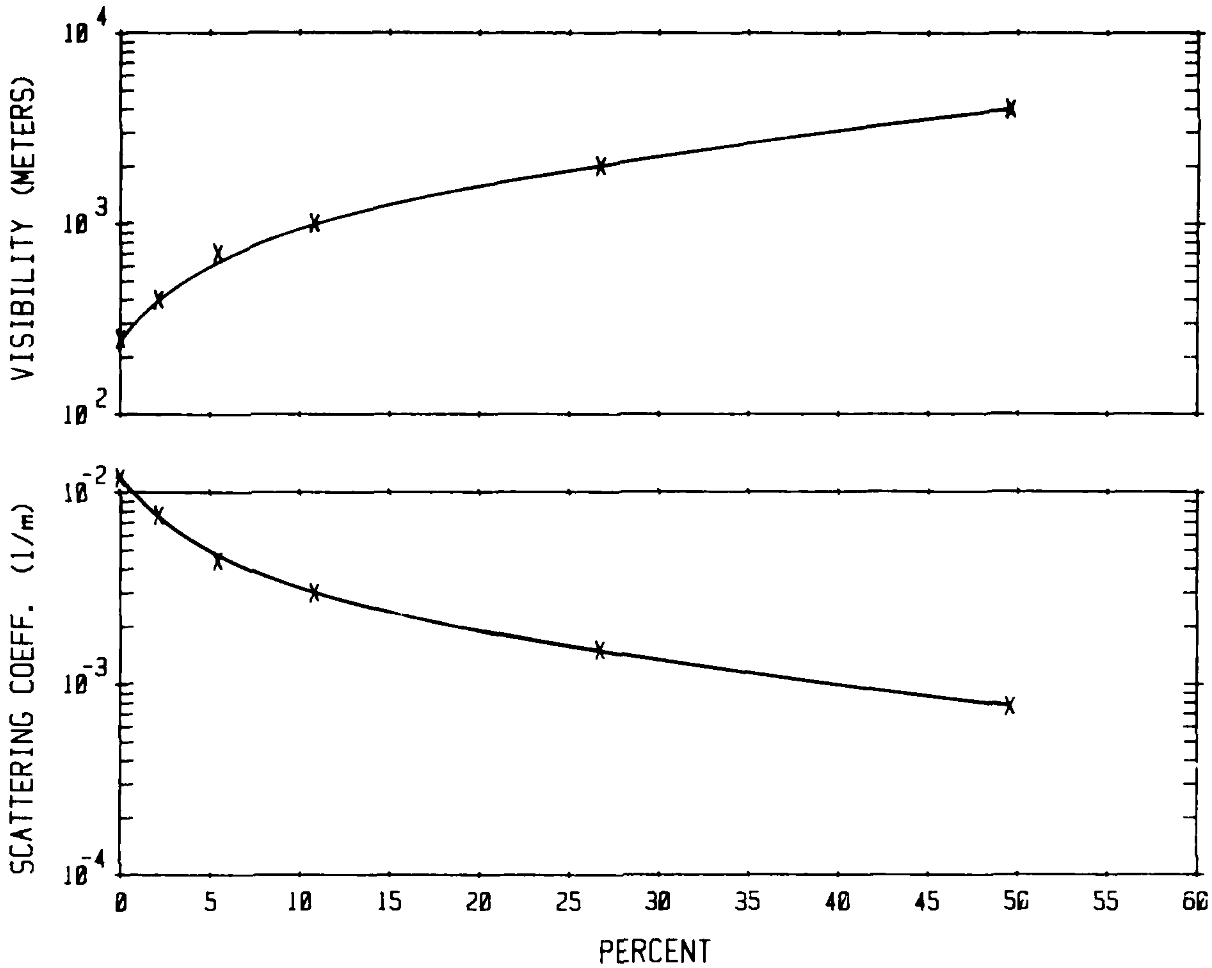


Figure 20. Percent of Time During Which Visibility was Less than Value Shown and Scattering Coefficient Exceeded Value Shown

To develop an opinion as to whether or not it is reasonable to expect sufficient concentrations of giant nuclei to account for observed scattering, we returned to our 23 February 1977 data from Stage 1 (Ref. 6 and 7) obtained under approximately the same conditions (wind speed 13 m/sec, wave height 2.8 m, RH 89 to 93%). The scattering coefficient was consistently 1 to 3×10^{-4} m^{-1}.

The only reasonable conclusion that we can draw, therefore, is that the observed scattering was not due to particles in equilibrium with the air parcels that they occupied. The particles must have grown to fairly large sizes in the short time during which the mixture was very highly saturated. By the time the air parcels were carried to the 7 m level where measurements were made, they were no longer saturated and droplets were evaporating. However, the time required for the air parcels to reach the 7 m level was so short that evaporation was not complete.

Epilog

The cold air outbreak responsible for the observed sea smoke was documented by two DMSP images of the eastern U.S. and Mexico obtained at approximately 1100 CST on 9 and 10 December. The images which are reproduced as Figures 21 and 22, constitute spectacular illustrations of the banded cloud formations produced when cold air passes over warm water. Both images illustrate the cellular structure of the banded clouds formed over the broad fetch of Lakes Superior and Huron, while the latter image shows the severe lake-effect snow storms in progress over Lakes Erie and Ontario. Early studies by Calspan (see, e.g., Ref. 26-28) describe these banded stratocumulus systems and their cellular structure when they develop to the snow storm stage. Observers along the shorelines of the Great Lakes have been impressed with the dense sea smoke that frequently precedes cloud formation and occasionally organize into small funnel clouds after strong convection becomes established.

It is interesting and perhaps important to note that even the largest of these lake-effect cloud bands is dwarfed by comparison to the bands that are evident over the Gulf of Mexico and the Atlantic Ocean in the 10 December DMSP image. The similarity in structure of individual bands within the three systems and the general conformance of the upwind envelope of the bands with the shore of the body of warm water leave little doubt that similar processes are responsible for their existence.

Similar situations have been noted by numerous authors in the past. In addition, we have observed similarities in the banded structure of the lake-effect cloud systems and the fog-stratus systems that frequently begin as cloud streets off the California coast (Ref. 3 and 14). We are now attempting to relate these systems to patches of warm water which exist within regions of cold upwelling water (Ref. 29). As a minimum, a climatological study of these potentially related phenomena appears warranted.

4.3 The Fog of 2 December 1978

Extensive fog occurred along the Florida panhandle coast on the morning of 2 December 1978. At Stage 1, fog occurred during two brief periods in the morning, for a total duration at the 25 m height of <2 hours. At the shoreline Beachtower Site, fog persisted for >4 hours. The visibility records for this fog are presented in Figure 23. This fog episode is particularly interesting in that sufficient information is available to permit the interrelation of synoptic scale, mesoscale and microscale phenomena.

During the two-day period preceding this fog, a stationary frontal system was located in the area. On November 30, the stationary front extended from the middle of the Gulf to just north of Tallahassee (TLH) continuing as a cold front to a low in the Atlantic off Cape Cod. The 500 mb pattern on 30 November showed a broad trough over the U.S., with trough axis centered over the Plains states. The 500 mb low was located over Hudson Bay. Precipitation was associated with this front and 24 hour totals ending at 0600 CST on 30 November throughout the Southeast were about 0.25 inches.

A wave developed on this stationary front at 1800 CST on 30 November (along the coastline) over Panama City, FL. The wave subsequently moved northeastward over TLH and was situated just north of Jacksonville, FL, at 0600 CST on 1 December. Wave development was associated with the eastward movement of the 500 mb trough. The trough axis was located through central Mississippi, and northward along the Mississippi river at 0600 CST, 1 December. The 850 mb chart at 0000Z, 2 December (1800 CST, 1 Dec) showed a temperature wave over the Gulf coastal states. The 850 mb pattern does not show a substantial

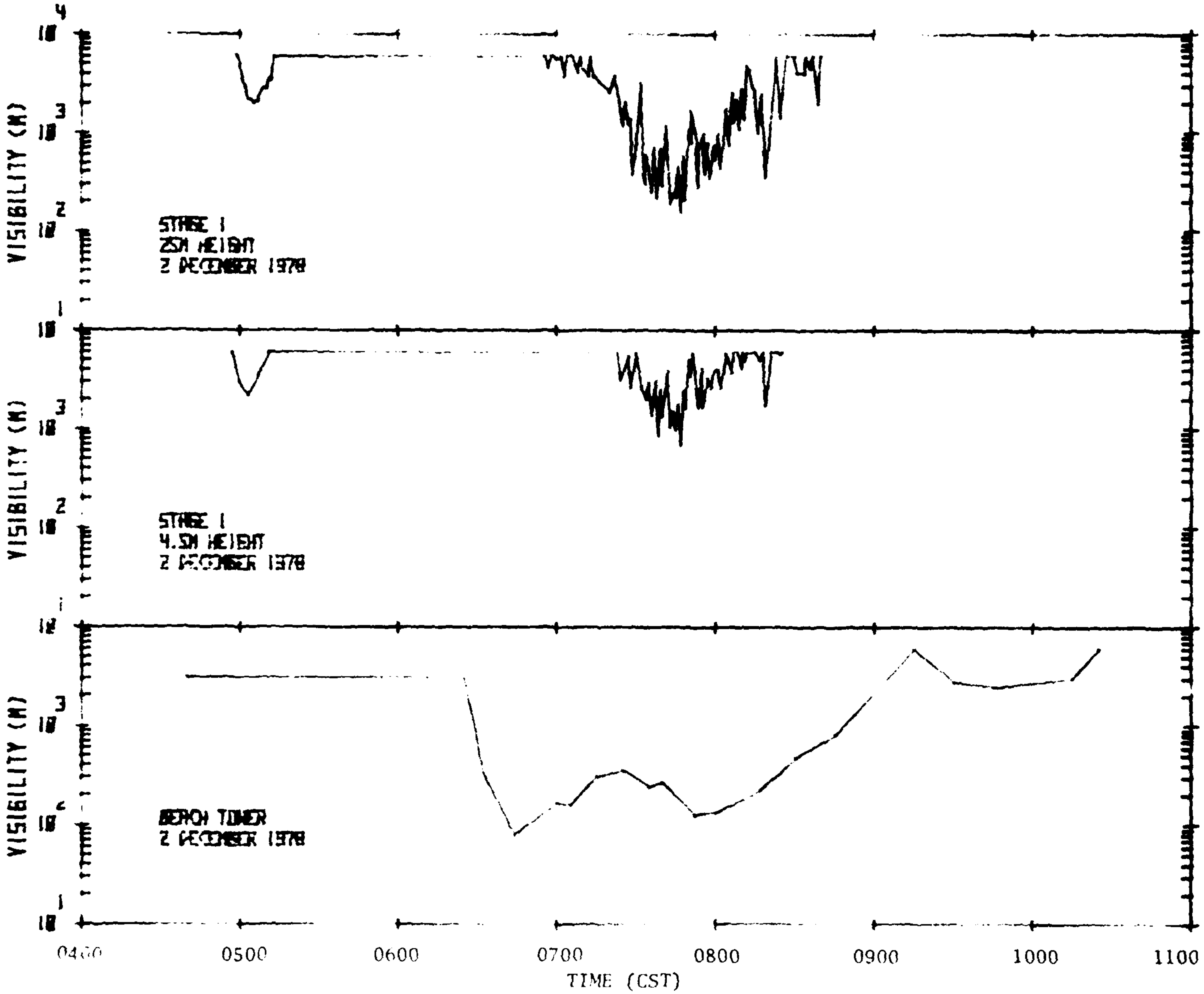


Figure 23. Visibility at the Shoreline and at Two Heights on Stage I During the Fog of 2 December 1978

short wave, but the winds at 850 mb suggest the beginnings of a trough with its axis from just north of Little Rock to just north of Jackson, Mississippi and southward over Mobile.

The surface low moved from Jacksonville rapidly into the Atlantic during the day on 1 December. Behind this system, a high pressure ridge filled in over the SE U.S., with generally weak N.E. gradient (drainage winds) over the southeast. The surface pressure pattern at 0700 CST on 2 December is depicted in Figure 24, reprinted from The National Weather Service Daily Weather Map series. No precipitation occurred in the immediate vicinity of Stage I for the 24 hour period ending 0600 CST on 2 December.

Figure 25 presents an analysis of winds at 0600 CST in the Southeastern U.S. and northern Gulf of Mexico in which the Stage I and Beachtower winds are added to data available from Figure 24. The axis of the ridge is well defined by the region of calm extending from central Mississippi to North Carolina. The cross-isobaric flow in continental regions southeast of the ridge, presumably stimulated by nocturnal cooling, converges at the coast with gradient induced winds that persist over the water.

The 600-meter thick, unstable boundary layer along the coast was capped by a subsidence inversion with dry air aloft through 1 December as shown by the soundings in Figure 26a. By midnight (Figure 26b), nocturnal cooling on land had produced a 200 m thick surface based inversion beneath the subsidence inversion. During the day, however, an influx of maritime surface air from the south increased the coastal dewpoint from approximately 6°C to 10°C in the layer between 100 and 600 m. (Compare the Eglin soundings in Figures 26a and b.) Thus, a situation developed in which surface temperatures colder than 10°C were separated vertically from air with dewpoint warmer than 10°C by distances of less than 200 m.

Any process which could cause the mixing of these two air masses could, therefore, produce the initial condensation aloft, and radiation from condensed moisture could cause the fog to propogate. We submit that the convergence pattern depicted in Figure 25 could easily have stimulated the

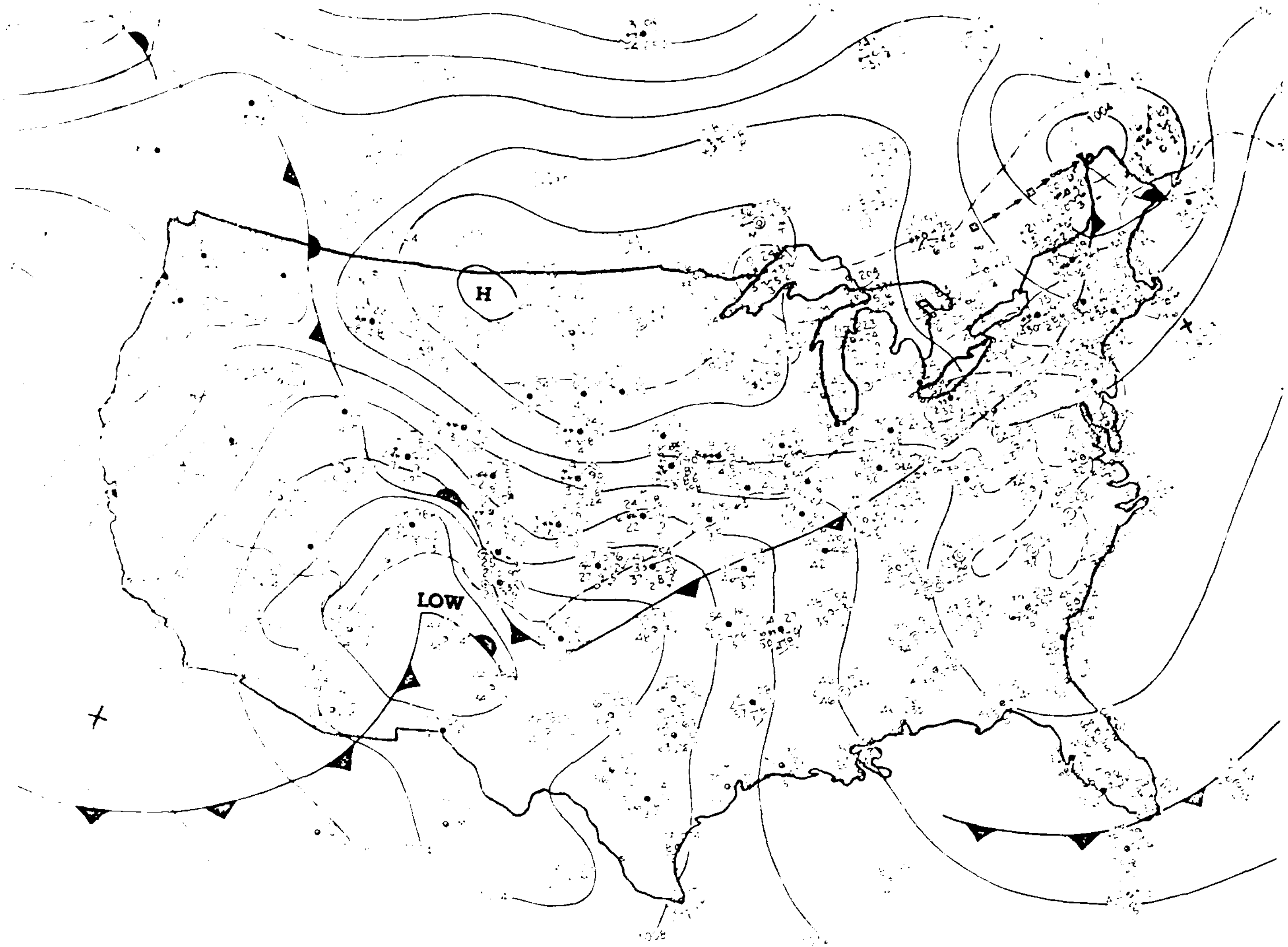


Figure 24. Surface Analysis for 0600 CST, 2 December 1978 (Daily Weather Map Series: NOAA)

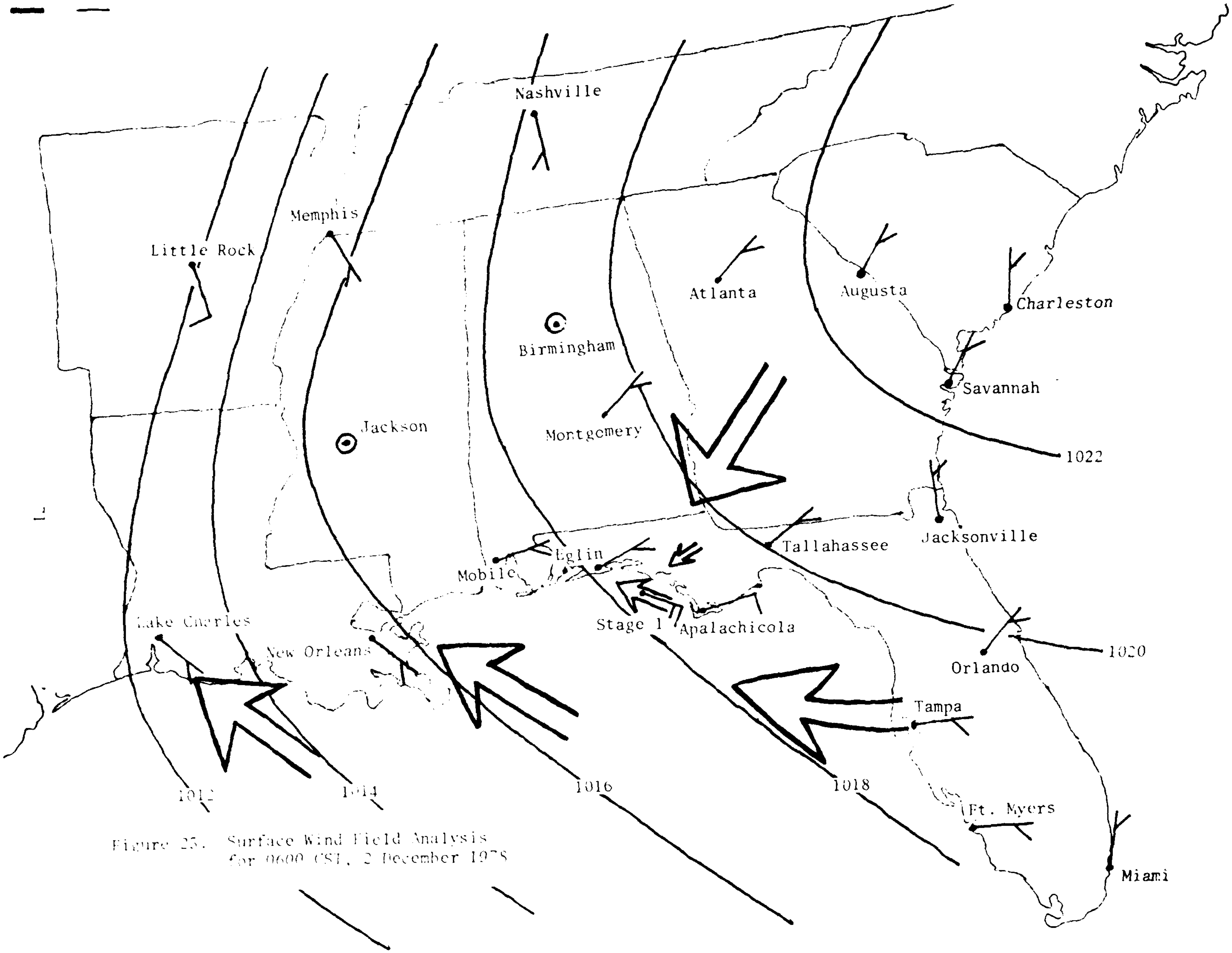
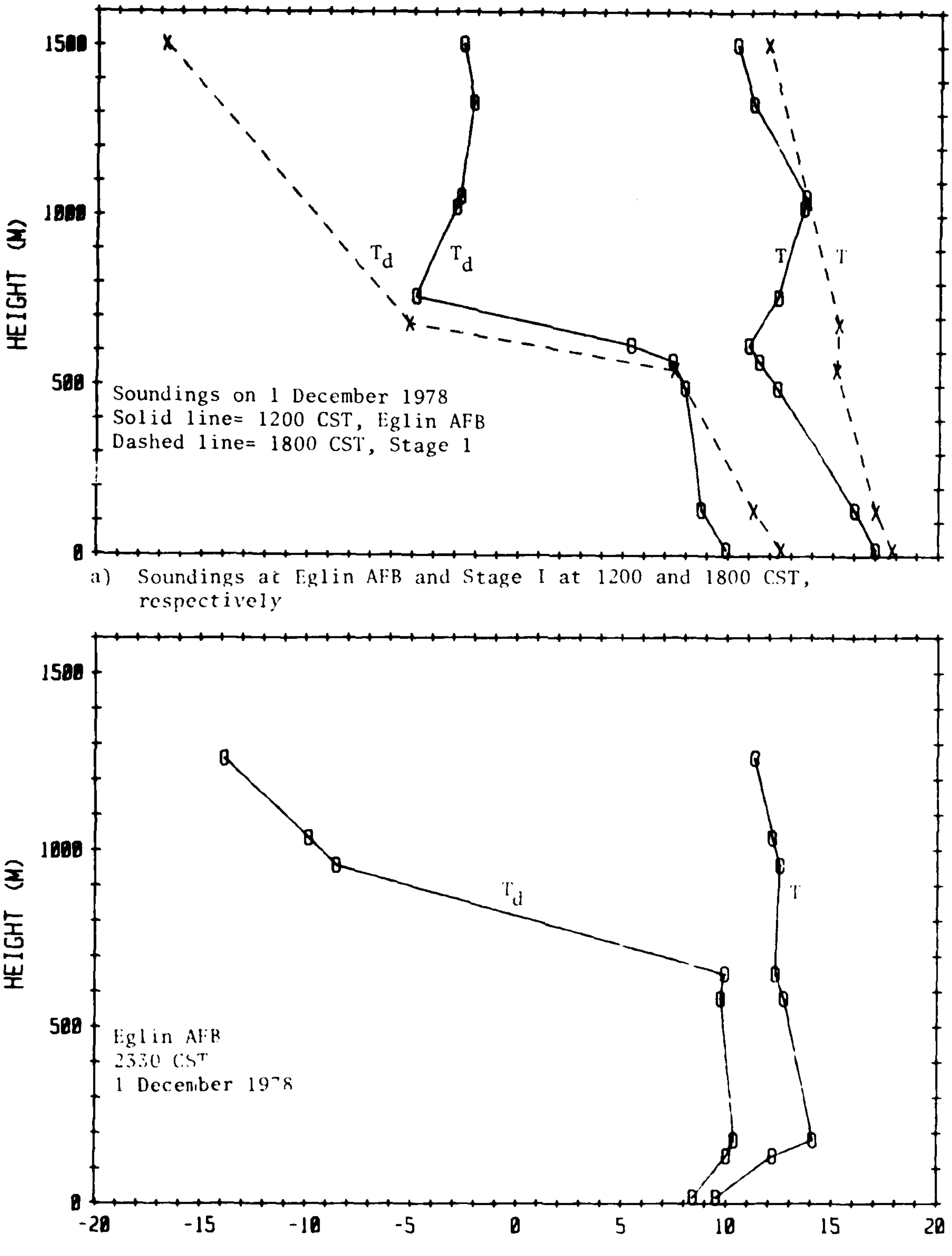


Figure 25. Surface Wind Field Analysis for 0600 CST, 2 December 1978



a) Soundings at Eglin AFB and Stage I at 1200 and 1800 CST, respectively

b) Sounding at Eglin AFB, 2330 CST

Figure 26. Temperature and Dewpoint Data Aloft on 1 December 1978

necessary mixing, and it is believed that the fog of 2 December along the coastline formed in this manner. As shown in Figure 27, cold and warm moist air masses did not exist in such vertical proximity over Stage I at 0630 CST. Fog patches observed immediately before and after that sounding apparently advected, with ESE winds, to that location from the Apalachicola Peninsula.

4.4 The Fog of 8 December 1978

Fog formation in coastal areas is the result of several different processes, each associated with a particular synoptic situation. As described earlier for example, the fog of 2 December was associated with the presence of a high pressure ridge. The fog of 8 December described in the following discussion, formed by a different process associated with a different location of a high pressure ridge. This fog formed by a stratus lowering process.

Synoptic

A common factor in the synoptic pattern of both the 2 December and 8 December fogs was the presence of a high pressure ridge in the southeastern United States. The location of the ridge in relation to the coastal region has a major influence on the process of fog formation. For example, in the discussion of the 2 December fog, it was shown that a ridge to the north and northeast of the coast produced a weak gradient situation over land, resulting in drainage winds off the land. Convergence was set up along the coast by weak gradient flow over the Gulf and together with radiational cooling, resulted in a fog. In the 8 December fog, the region is again influenced by a ridge, but the ridge is located to the east of the coastal area, allowing onshore gradient winds to establish a marine layer in the lower atmosphere in the coastal zone. Figure 28, reprinted from the *Daily Weather Map* series, shows this situation.

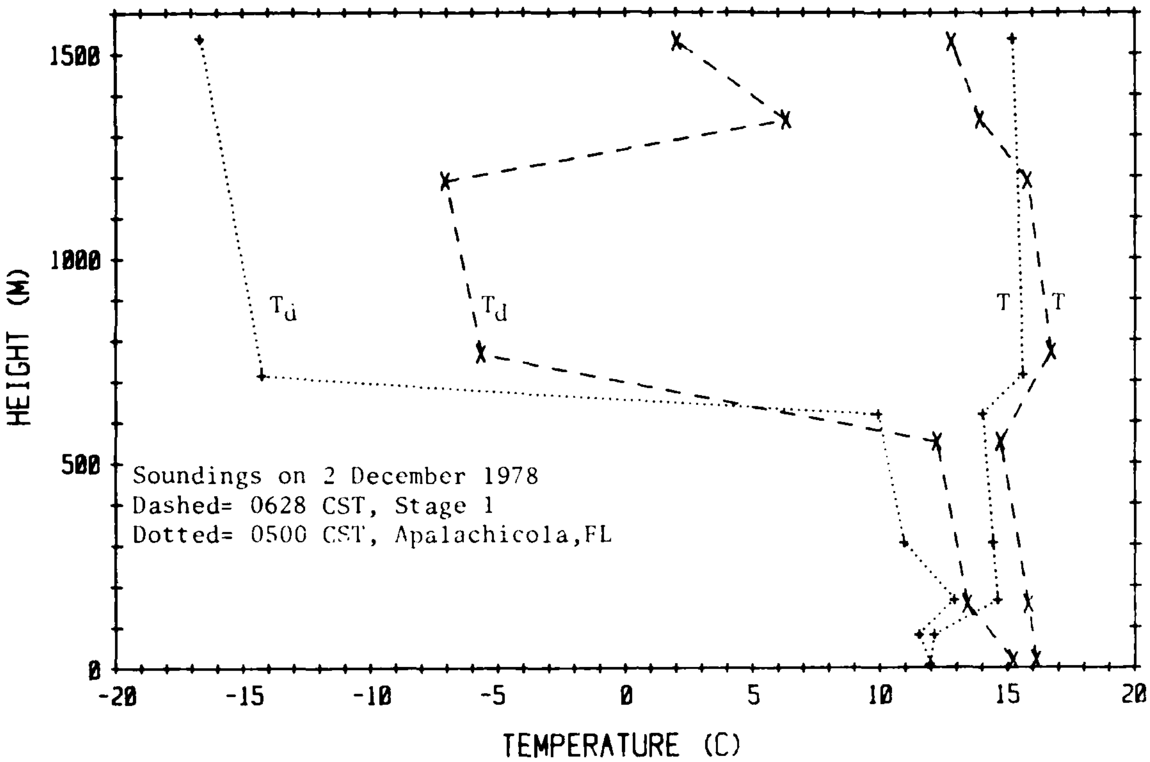


Figure 27. Soundings from Apalachicola, FL, and Stage I at 0500 and 0628 CST, respectively, on 2 December 1978

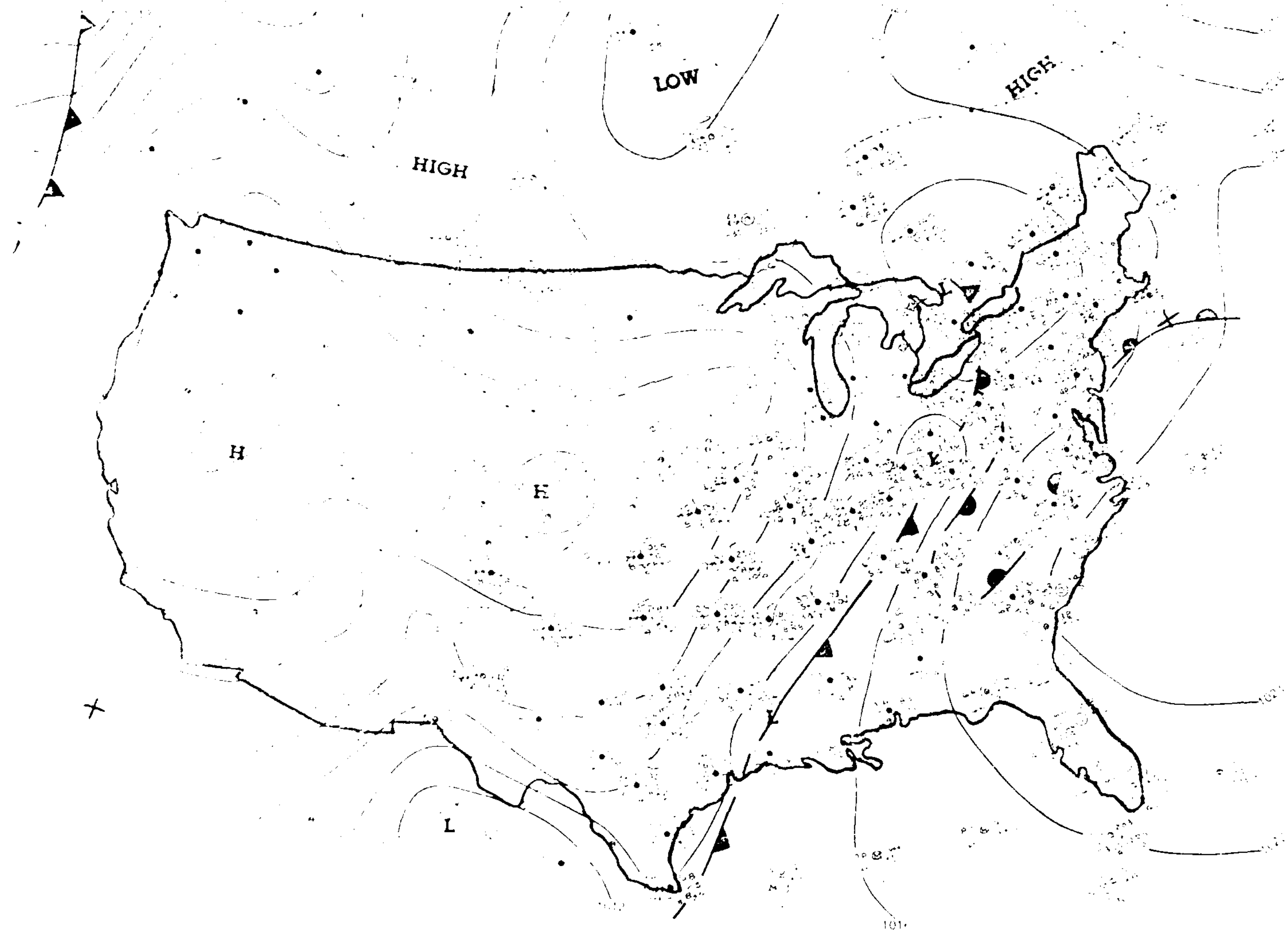


Figure 28. Surface Analysis for 0600 CST, 8 December 1978 (Daily Weather Map Series: NOAA)

Description of Fog Episode

Haze and low broken stratus were reported during the day of 7 December. Towards evening, visibilities began to gradually decrease. Fog was not reported at either the Beach site or Stage I until ~0100 CST on 8 December. However, Eglin AFB observations show a reduction of visibility to 400 m at 2130 CST on 7 December and then an increase in visibility to 5000 m by 0030 CST on 8 December. This drop in visibility was not detected at the Beach site nor on Stage I. At 0030, visibility at the Beach site dropped below 600 m. Fog patches were observed at the 20 m level on Stage I at 0050*, but the visibility at 4.5 m MSL did not drop below 6000 m until 0210 CST. Figure 29 shows the visibility records obtained at the Beach and Stage I on 8 December. Observations from Eglin AFB show that visibility once again began to drop, reaching 1000 m at 0300 CST. A minimum visibility of 100 m occurred at Eglin at 0630 CST. By this time, the fog had already ended at Stage I and the Beach site. (Fog persisted at Eglin until 0900 CST.) The visibility record from Stage I reflects the sequence of visibility restriction typical of stratus-lowering fogs; visibility restriction occurs first and is greatest at higher levels.

Fog Formation Process

A stratus lowering fog can be identified by several characteristics, as outlined by Mack, Pilié and Katz (Ref. 3):

1. Radiational cooling at stratus top, resulting in a capping inversion at an altitude of <400 m and liquid water increase at the top of the cloud.

2. Increase in stability immediately above cloud top; instability within the cloud which eventually extends below the cloud base.

3. Turbulent transfer downward of air parcels from cloud top to mix with clear air beneath cloud, causing the cloud (visibility restriction) to propagate downward.

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*Instrument malfunction prevented visibility data acquisition at the 25 m level prior to ~0320 CST.

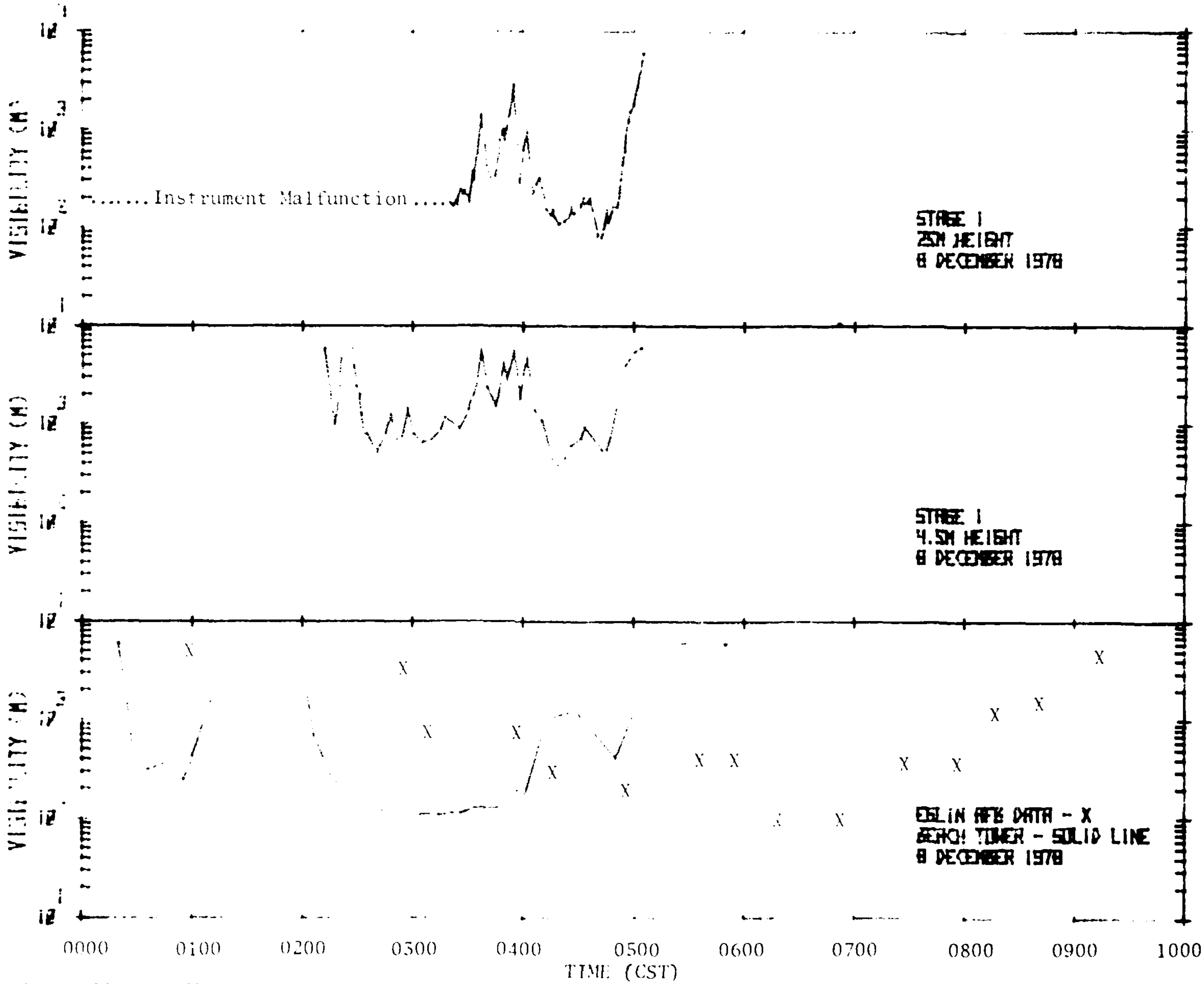


Figure 29. Visibility at Stage I, Beach Tower, and Eglin AFB During the Fog of 8 December 1978

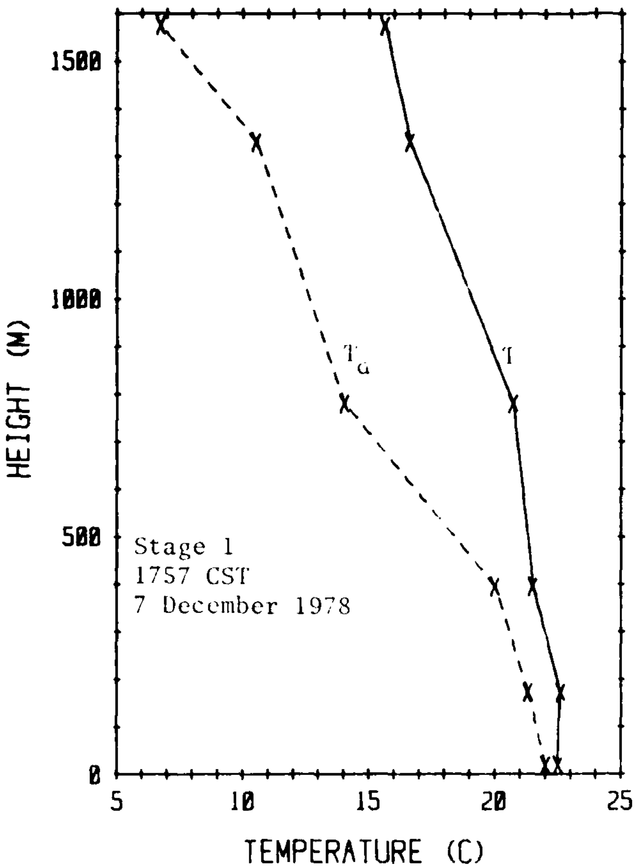
The soundings taken before and during the fog at Stage I are shown in Figure 30. The capping inversion above the stratus top is based at a height of ~ 375 m at 0143 CST. The inversion layer (~375-460 m) is the stable region above the cloud while a lapse rate of ~6°C/km exists from just below the inversion to the surface. Since parcels below the inversion would follow the moist adiabatic lapse rate of ~4.5-5°C/km, this region, extending to the surface, is unstable.

The result of radiative cooling can also be detected in the layer beneath the inversion. By comparing the pre-fog (1757 CST) sounding with the 0143 CST sounding during the fog, it is evident that a general cooling took place over the entire air column. Superimposed on this is the radiative cooling, occurring below 375 m. Some rates of cooling at various heights between sounding times are shown below.

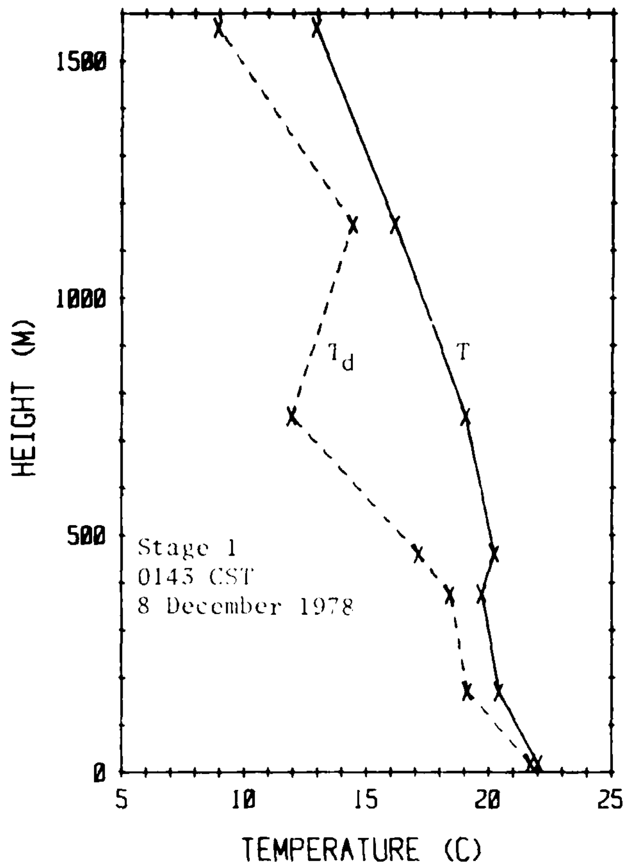
Height (m)	Cooling rate (°C/8 hrs)
12	.5
200	2
300	2
375	2
460	1.2
650	1.5

As shown by the table, the effect of radiative cooling shows up in the layer 200 to 300 m. If the cooling rate at 650 m is taken to be the amount of cooling experienced by the entire sounding, there is an additional 0.5°C of cooling occurring beneath the inversion due to radiation. It is obvious from the superadiabatic lapse in the lowest levels (caused by the very warm Gulf waters) that considerable heat is being transferred into the atmosphere, offsetting some of the effects of radiational cooling aloft.

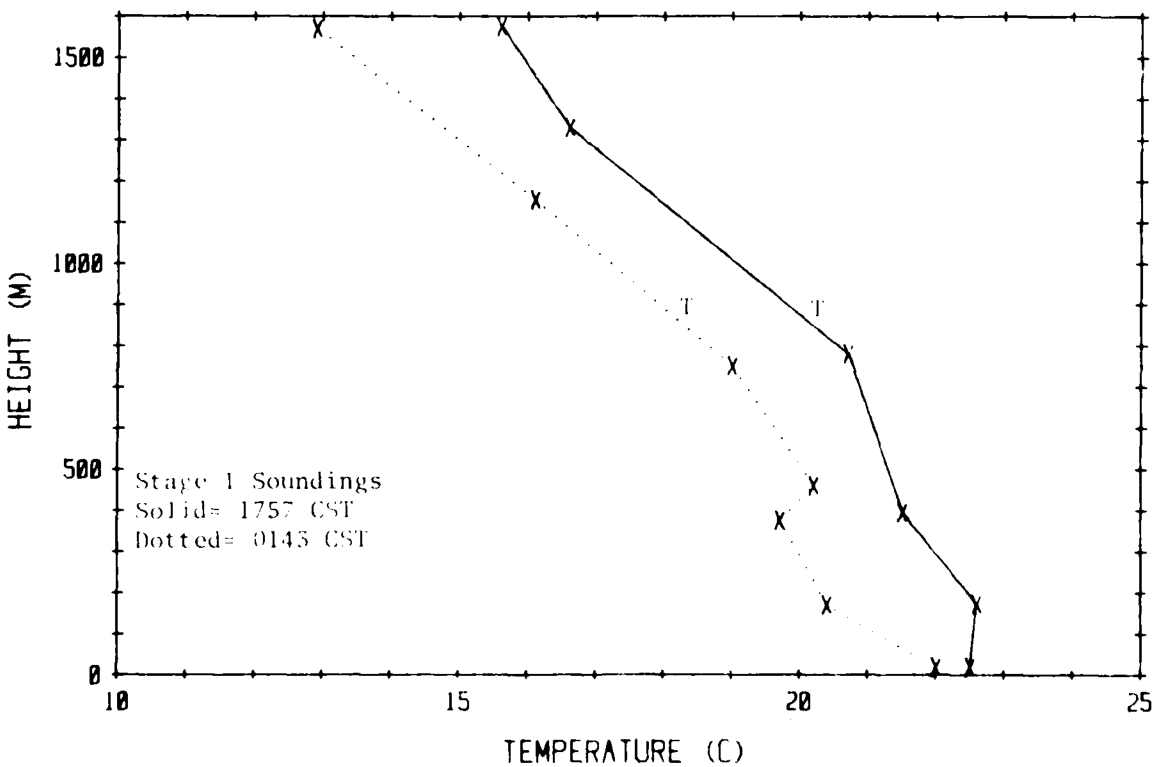
From this analysis of the sounding, all the features of a stratus lowering situation as described earlier are present in this fog.



a) Temperature and Dewpoint Sounding at 1757, 7 December



b) Temperature and Dewpoint Sounding at 0143, 8 December



c) Temperature Profiles at 1757, 7 December and 0143, 8 December

Figure 30. Temperature and Dewpoint Soundings at Stage I on 7 and 8 December 1978

Summary

A high pressure ridge to the east of the Gulf coast region caused a marine air mass to be established in the coastal zone by onshore winds. Low stratus present in this air mass propagated downward by a stratus lowering process once radiative cooling became effective at the top of the stratus deck. An analysis of soundings prior to and during the fog contain features consistent with a stratus lowering situation.

REFERENCES

1. Mack, E.J., R.J. Pilié, and W.C. Kocmond, 1973: "An Investigation of the Microphysical and Micrometeorological Properties of Sea Fog," Project SEA FOG, First Annual Summary Report, Calspan Report CJ-5237-M-1, May, 39 pp.

2. Mack, E.J., U. Katz, C.W. Rogers and R.J. Pilié, 1974: "The Microstructure of California Coastal Stratus and Fog at Sea," Report CJ-5404-M-1, July, 67 pp.

3. Mack, E.J., R.J. Pilié and U. Katz, 1975: "Marine Fog Studies Off the California Coast," Project SEA FOG: Third Annual Summary Report, Calspan Report No. CJ-5606-M-1, March, 80 pp.

4. Mack, E.J. and U. Katz, 1976: "The Characteristics of Marine Fog Occurring Off the Coast of Nova Scotia," Project SEA FOG: Fourth Annual Summary Report, Part 1, Calspan Report No. CJ-5756-M-1, June, 180 pp.

5. Mack, E.J. and C.W. Rogers, 1976: "Simulation of Marine Advection Fog with the Calspan Advection Fog Model Using Prognostic Equations for Turbulent Energy," Project SEA FOG: Fourth Annual Summary Report, Part 2, Calspan Report No. CJ-5756-M-2, June, 39 pp.

6. Mack, E.J. and U. Katz, 1977: "Measurements of Aerosol and Micrometeorological Characteristics of the Marine Boundary Layer in the Gulf of Mexico," Calspan Report, March, 59 pp.

7. Katz, U. and E.J. Mack, 1977: "Direct Measurements of Sea Spray Size Spectra at the NCSL Offshore Platform," Calspan Report No. CH-6067-M-1, April, 94 pp.

8. Katz, U. and E.J. Mack, 1977: "Measurements of Aerosol and Micrometeorological Characteristics of the Marine Boundary Layer during the Transatlantic/Mediterranean Cruise of the USNS Hayes, May-June 1977," Calspan Report, September.

9. Mack, E.J., U. Katz, C.W. Rogers, D.W. Gaucher, K.R. Piech, C.K. Akers, and R.J. Pilié, 1977: "An Investigation of the Meteorology, Physics, and Chemistry of Marine Boundary Layer Processes," Project SEA FOG: Fifth Annual Summary Report, Calspan Report No. CJ-6017-M-1, October, 123 pp.

10. Mack, E.J., Anderson, R.J., Akers, C.K., and Niziol, T.A., 1978: "Aerosol Characteristics of the Marine Boundary Layer of the North Atlantic and Mediterranean during May-June 1977" Project Sea Fog: Sixth Annual Summary Report, Calspan Report No. 6232-M-1, October, 215 pp.

11. Mack, E.J. and Niziol, T.A., 1978: "Reduced Data from Calspan's Participation in the CEWCOM-78 Field Experiment off the Coast of Southern California during May 1978" Project Sea Fog: Sixth Annual Summary Report, Calspan Report No. 6232-M-2, October, 93 pp.

12. Pilié, R.J., Mack, E.J., Rogers, C.W., Katz, U., and Koemond, W.C., 1978: "Off-Shore Fog-Stratus Systems Along the California Coast" Project Sea Fog: Special Report, Calspan Report No. 6232-M-3, December, 48 pp.

13. Niziol, T.A. and E.J. Mack, 1979: "Reduced Data from Calspan's Participation in the Panama City II Field Experiment in the Northern Gulf of Mexico during November-December 1978" Calspan Report No. 6467-M-1, April, 187 pp.

14. Pilie, R.J., E.J. Mack, C.W. Rogers, U. Katz and W.C. Koemond, 1979: "The Formation of Marine Fog and the Development of Fog-Stratus Systems Along the California Coast," J. Appl. Met., 36, 10, October.

15. Mack, E.J., T.A. Niziol, C.W. Rogers and C.K. Akers, 1979: "Meteorological and Aerosol Characteristics of the Marine Boundary Layer in the Vicinity of San Nicolas Island During CEWCOM-78" Calspan Report No. 6437-M-1, December, 127 pp.

16. Mack, E.J., Akers, C.K. and Niziol, T.A., 1980: "Aerosols in the Marine Boundary Layer" Proceedings of the Second Conference on Coastal Meteorology, 30 January - 1 February, Los Angeles, CA.

17. Akers, C.K. and E.J. Mack, 1980: "The Microphysics and Chemistry of Sea Spray and Marine Aerosols in the Northern Gulf of Mexico, Calspan Report No. 6458-M-1, August, 60 pp.

18. Petterssen, S., 1938: "On the Causes and the Forecasting of the California Fog," Bull. of the Amer. Met. Soc., Vol. [illegible], No. 2, pp. 49-55.

19. Rogers, C.W., E.J. Mack, U. Katz, C.C. [illegible], and R.J. Pilie, "The Life Cycle of California Coastal Fog on Shore," Calspan Report CJ-5076-M-3, August, [illegible] pp.

20. Leipper, D.F., 1948: "Fog Development at San Diego, Calfornia," Sears Foundation; Journal of Marine Research, 7, 3, pp. 337-346.

21. Mack, E.J., W.J. Eadie, C.W. Rogers, W.C. Kocmond and R.J. Pilié, 1973: "A Field Investigation and Numerical Simulation of Coastal Fog," NASA, CR-2201, February, 136 pp.

22. Anderson, J.B., 1931: "Observations from Airplanes of Cloud and Fog Conditions Along the Southern California Coast," Mon. Weather Review, July, 1931, pp. 264-270.

23. Deardorff, J.W., 1979: "Prediction of Convective Mixed-Layer Entrainment for Realistic Capping Inversion Structure," J. Atm. Sci., 36, 3, March, pp. 424-436.

24. Rogers, C.W. and J.T. Hanley, 1980: "An Algorithm for the Increase of Liquid Water Content with Height in Fog and Water Hazes," Calspan Report No. 6711-M-1, September, 14 pp.

25. Taylor, G.I., 1917: "The Formation of Fog and Mist," Quart. J. Royal Meteor. Soc., 43, pp. 241-268.

26. McVehil, G.E., C.W. Rogers, and W.J. Eadie, 1968: The Structure and Dynamics of Lake-Effect Snowstorms. Final Report on Contract No. E22-89-68(N), CAL Report No. VC-2529-P-1, Cornell Aeronautical Laboratory, Inc., Buffalo, New York.

27. Eadie, W.J., R.J. Pilié, and W.C. Kocmond, 1971a: Modification and Modeling of Lake-Effect Weather. Final Report on Contract No. E22-39-70(N), CAL Report No. VC-2898-P-2, Cornell Aeronautical Laboratory, Inc., Buffalo, New York.

28. Eadie, W.J., U. Katz, and C.W. Rogers, 1971b: Investigations of Lake-Effect Snowstorms. Final Report on Contract No. E22-59-71(N), 29 November 1971. CAL Report No. VC-3034-M-1, Cornell Aeronautical Laboratory, Inc., Buffalo, New York.

29. Rogers, C.W. and J.T. Hanley, 1979: "Deformation of the Marine Inversions and the Development of Marine Fog and Stratus Resulting from Warm Water Patches: Numerical Modeling and Verifications with Satellite Imagery, Calspan Report No. 6612-M-1, November, 27 pp.

Appendix A

FOG LOG: A LISTING OF FOGS OBSERVED AT SEA TO DATE ON THIS PROGRAM

Date	Location	Fog Type	Avg. Min. Visibility
26 Aug '72	MTY Bay	Stratus Lowering	1.5 km
29-30 Aug '72	Farallon Islands	Stratus Lowering	1.0 km
30 Aug '72	Farallon Islands	Stratus Lowering	1.0 km
30 Aug '72	Farallon Islands	Warm Water	[illegible] km
31 Aug '72	Coastal near San Francisco	Coastal Radiation	1.0 km
9-10 July '73	Vandenberg	Warm Water	0.5 km
10 July '73	Vandenberg	Warm Water	0.2 km
24 July '73	MTY Bay	Coastal Radiation	0.2 km
25 July '73	MTY Bay	Coastal Radiation	0.2 km
26 July '73	MTY Bay	Coastal Radiation	0.2 km
29 Apr '74	MTY Bay	Coastal Radiation	0.5 km
30 Apr '74	MTY Bay	Coastal Radiation	0.5 km
7 May '74	MTY Bay	Stratus Lowering	1.5 [illegible]
8 May '74	MTY Bay	Stratus Lowering	1.0 km
11 May '74	MTY Bay	Coastal Radiation	0.5 km
22 Aug '74	Eureka	Convergence	0.1 km
23 Aug '74	To 40 nmi Offshore Eureka	Fog Patches (numerous)	[illegible] km
24 Aug '74	Eureka	Shallow Coastal (numerous)	0.5 km
24 Aug '74	To 50 nmi Offshore Eureka	Fog Patches (numerous)	[illegible] km
24 Aug '74	65 nmi Offshore Eureka	Warm Water (single)	0.2 km
25 Aug '74	60 nmi Offshore Eureka	Warm Water (single)	[illegible]
26 Aug '74	Cape Mendocino	Convergence	0.2 km
26-27 Aug '74	Cape Mendocino	Convergence	[illegible]
1 Sept '74	MTY Bay	Coastal Radiation	[illegible]
2 Sept '74	MTY Bay	Coastal Radiation	0.2 km
4 Sept '74	MTY Bay	Coastal Radiation	0.1 km

FOG LOG (Cont.)

Date	Location	Fog Type	Avg. Min. Visibility
2-3 Aug '75	35 n mi off Nova Scotia	Cold Water	0.10 km
3-4 Aug '75	30 n mi off Nova Scotia	Stratus Lowering Augumented by Cold Water	0.20 km
4-5 Aug '75	50 n mi off Nova Scotia	Cold/Warm Water	0.15 km
6-7 Aug '75	40 n mi off Nova Scotia	?	0.15 km
7 Aug '75	50 n mi off Nova Scotia	?	0.15 km
7 Aug '75	60 n mi SE of Nova Scotia	?	0.08 km
7-8 Aug '75	~150 n mi S of Newfoundland	Stratus Lowering	0.08 km
8-9 Aug '75	~150 n mi S of Newfoundland	Stratus Lowering	0.25 km
9 Aug '75	~150 n mi S of Newfoundland	Stratus Lowering	0.10 km
10 Aug '75	~150 n mi S of Newfoundland	?	0.15 km
11 Aug '75	~150 n mi S of Newfoundland	?	0.20 km
27-28 Sep '76	100 n mi SW of Pt. Conception, CA	Frontal (?)	0.20 km
5 Oct '76	Los Angeles	Coastal Radiation	0.15 km
8 Oct '76	10 n mi off Vandenberg	Cold Water (?)	0.10 km
9 Oct '76	45 n mi off Vandenberg	Stratus Lowering	0.8 km
13 Oct '76	75 n mi S of Santa Barbara	?	0.10 km
14 Oct '76	15 n mi off Vandenberg	Coastal Radiation	0.15 km

FOG LOG (Cont.)

Date	Location	Fog Type	Avg. Min. Visibility
14 May '78	Off San Nicolas Island	?	0.12 km
19 May '78	∿30 n mi SW of San Nicolas Island	?	0.20 km
20 Nov '78	Stage I, 12 n mi off Panama City, Fla.	?	3.0 km
24 Nov '78	Stage I, 12 n mi off Panama City, Fla.	?	4.5 km
2 Dec '78	Stage I, 12 n mi off Panama City, Fla.	Convergence	1.0 km
3 Dec '78	Stage I, 12 n mi off Panama City, Fla.	?	4.7 km
8 Dec '78	Stage I, 12 n mi off Panama City, Fla.	?	0.7 km
9-10 Dec '78	Stage I, 12 n mi off Panama City, Fla.	Sea Smoke	0.5 km

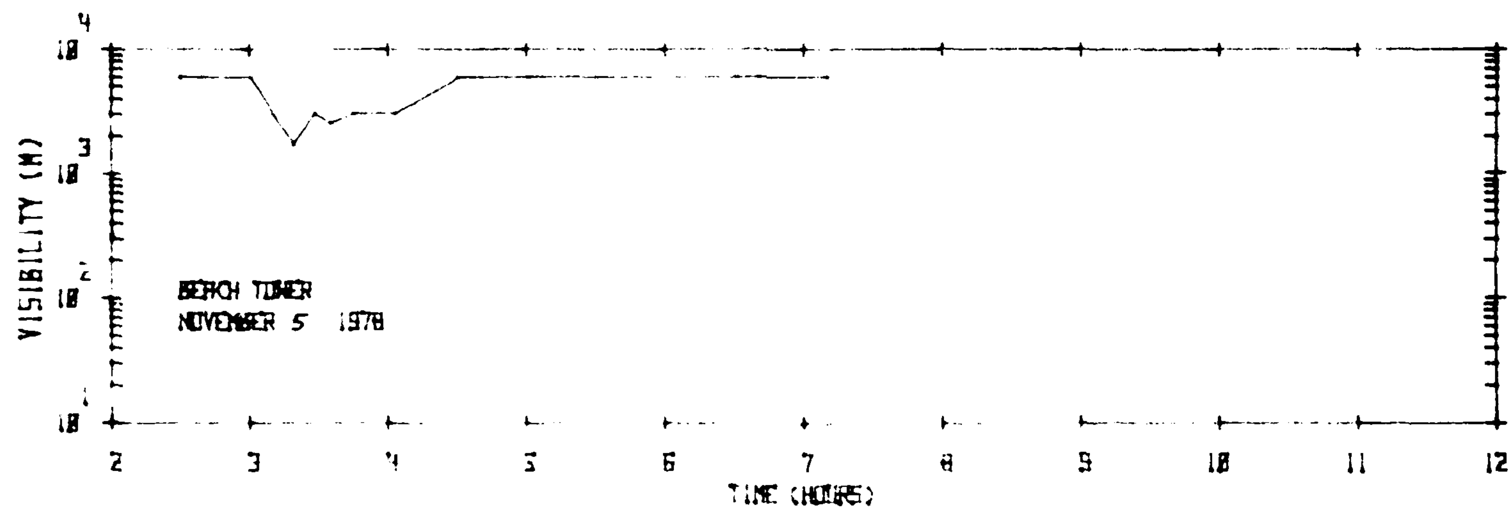
Fogs Observed on shore at Vandenberg AFG under Air Force Contract

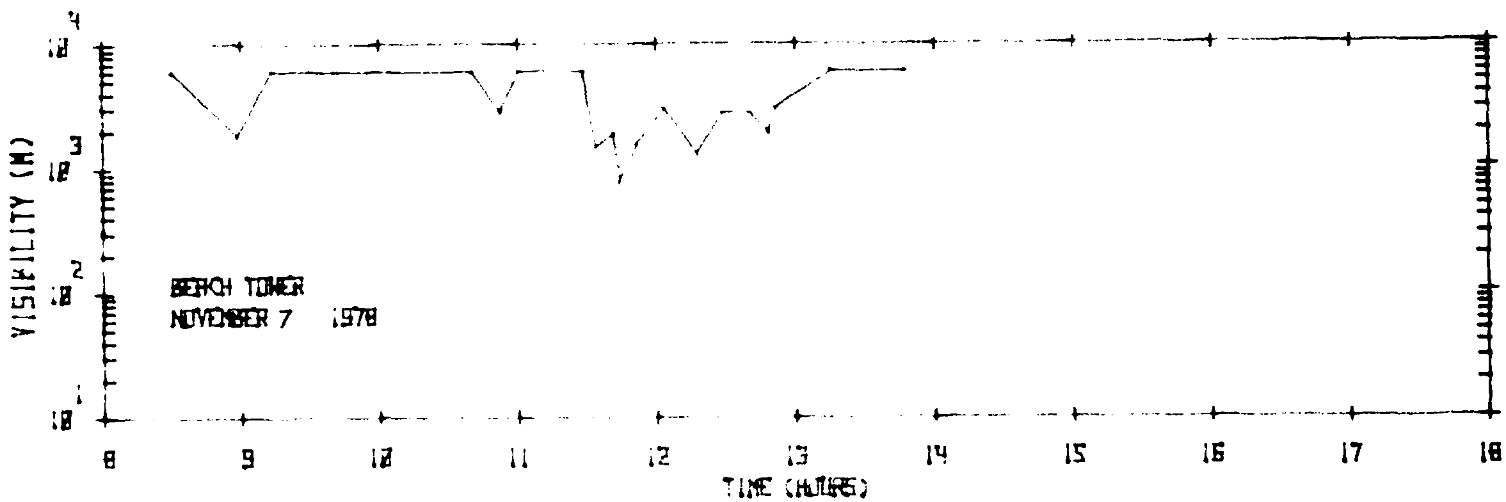
11-12 Jul '72	Vandenberg AFB, CA 1.0 n mi inland	Stratus Lowering	0.20 km
12-13 Jul '72	"	"	0.25 km
13-14 Jul '72	"	"	0.25 km
14-15 Jul '72	"	"	0.25 km
15-16 Jul '72	"	"	0.40 km
26-27 Jul '72	"	"	0.95 km
27-28 Jul '72	"	"	0.25 km
28-29 Jul '72	"	"	0.35 km
29-30 Jul '72	"	"	0.25 km
30-31 Jul '72	"	"	0.30 km

APPENDIX B

VISIBILITY DATA FOR FOGS WHICH OCCURRED DURING THE PANAMA CITY II EXPERIMENT

1 Nov - 12 Dec 1978


VISIBILITY (M)
TIME (HOURS)
BEACH TOWER
NOVEMBER 5 1978



BEACH TOWER
NOVEMBER 7 1978
VISIBILITY (M)
10^4
10^3
10^2
10^1
10^0
8
9
10
11
12
13
14
15
16
17
18
TIME (HOURS)

AD-A097 338 CALSPAN ADVANCED TECHNOLOGY CENTER BUFFALO NY F/G 4/2
AN INVESTIGATION OF MARINE FOG FORECAST CONCEPTS.(U)
JAN 81 C W ROGERS, E J MACK, R J RILIE N00019-80-C-0248
UNCLASSIFIED CALSPAN-6673-M-1 NL

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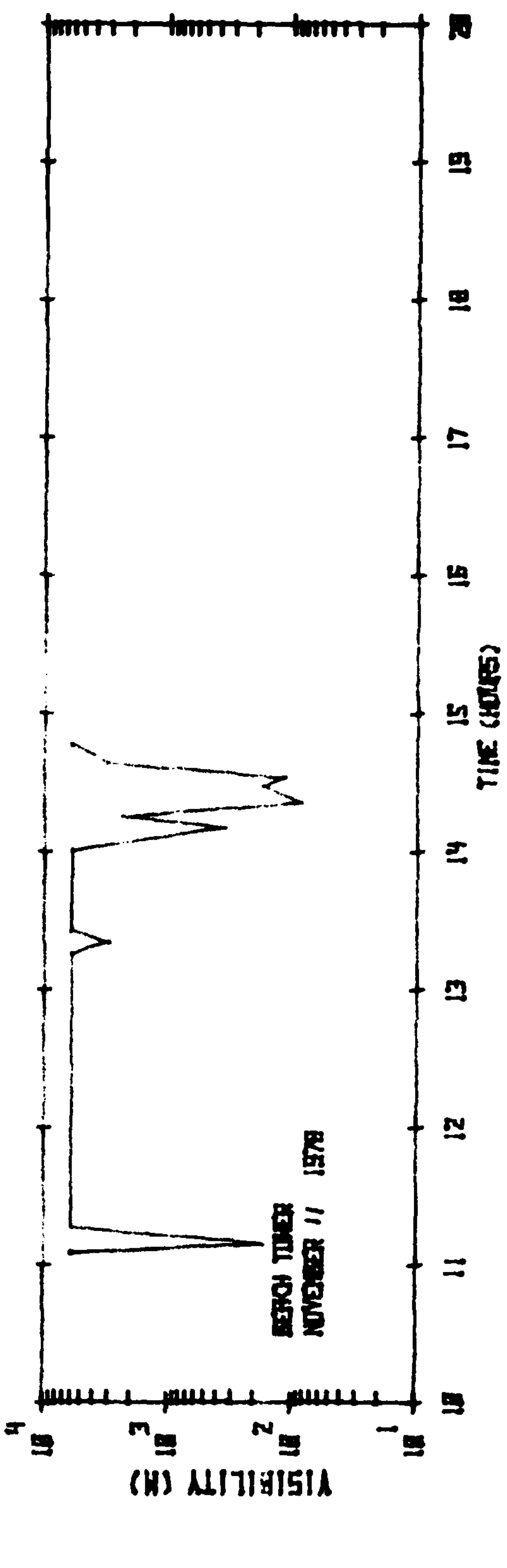
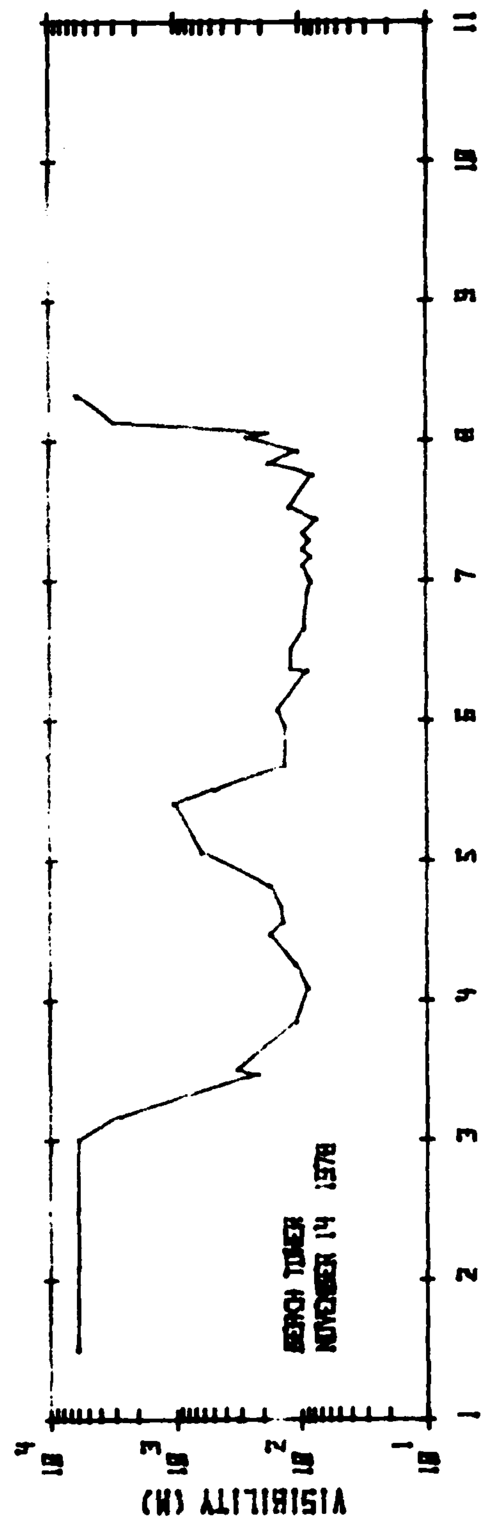
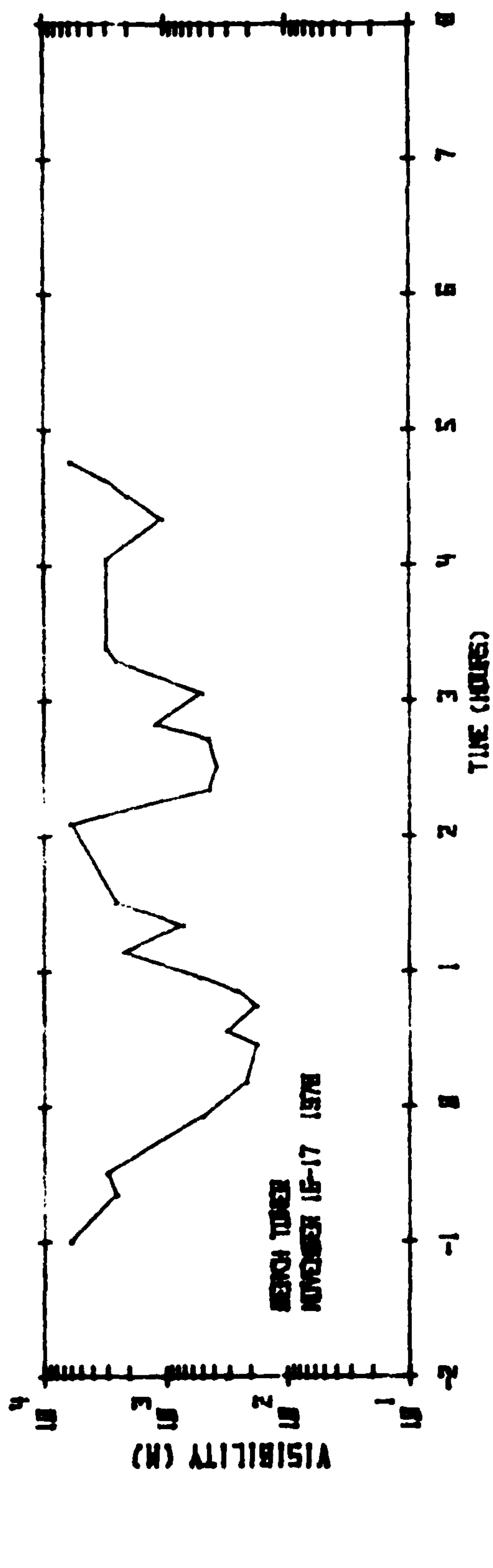
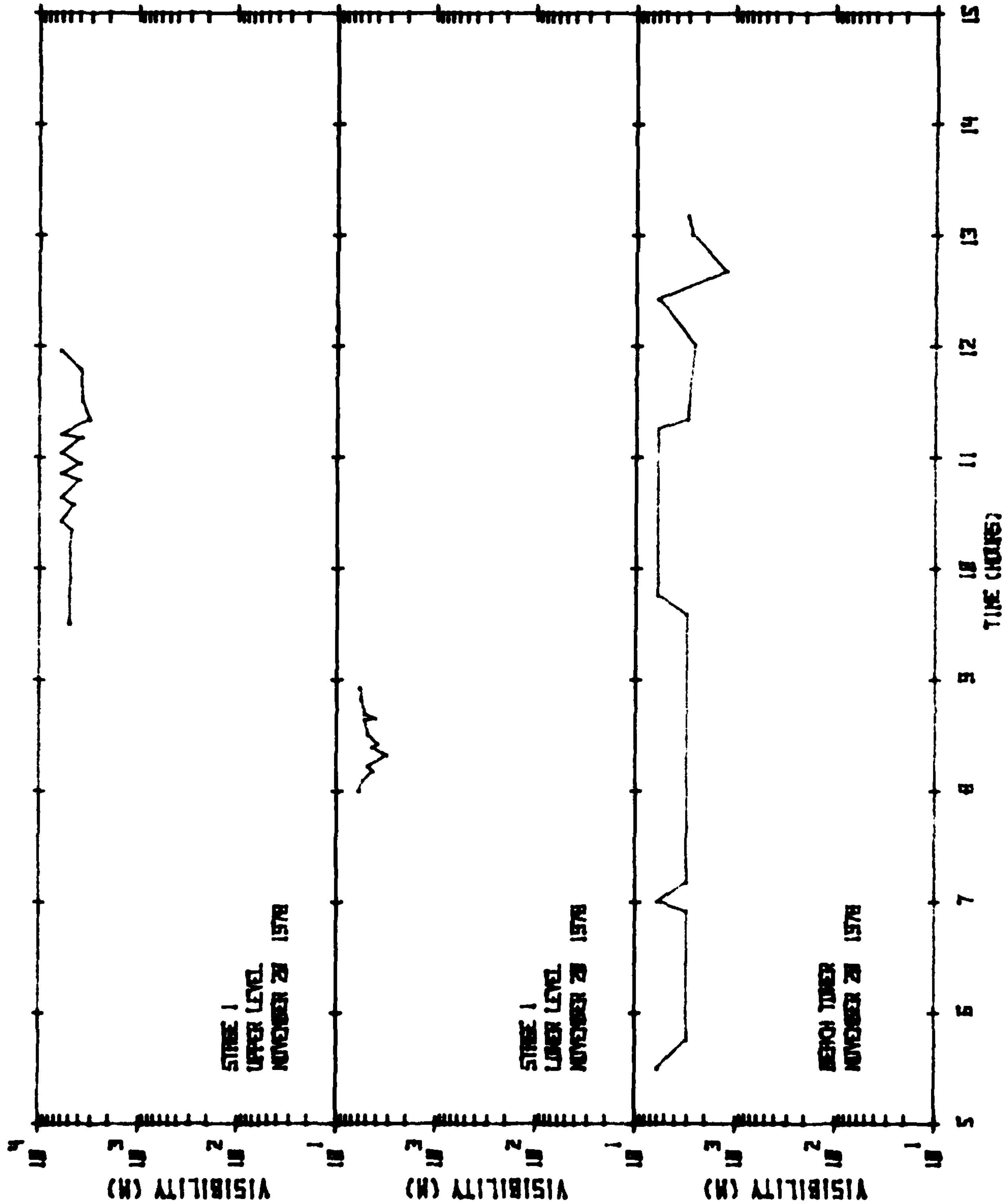
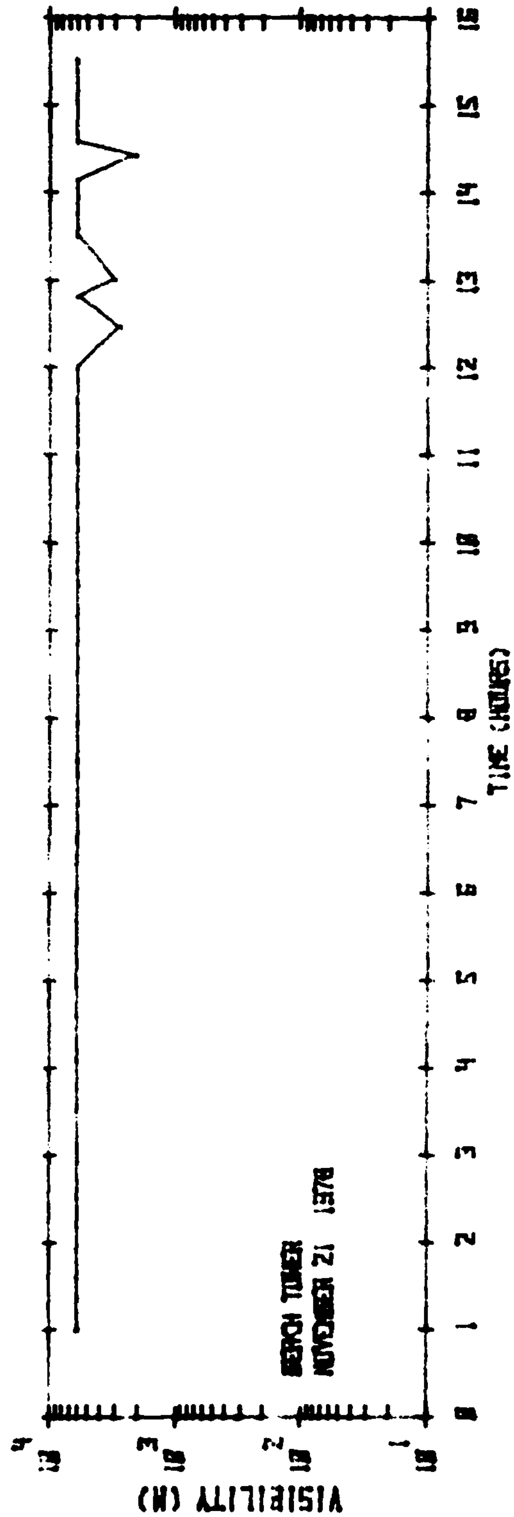
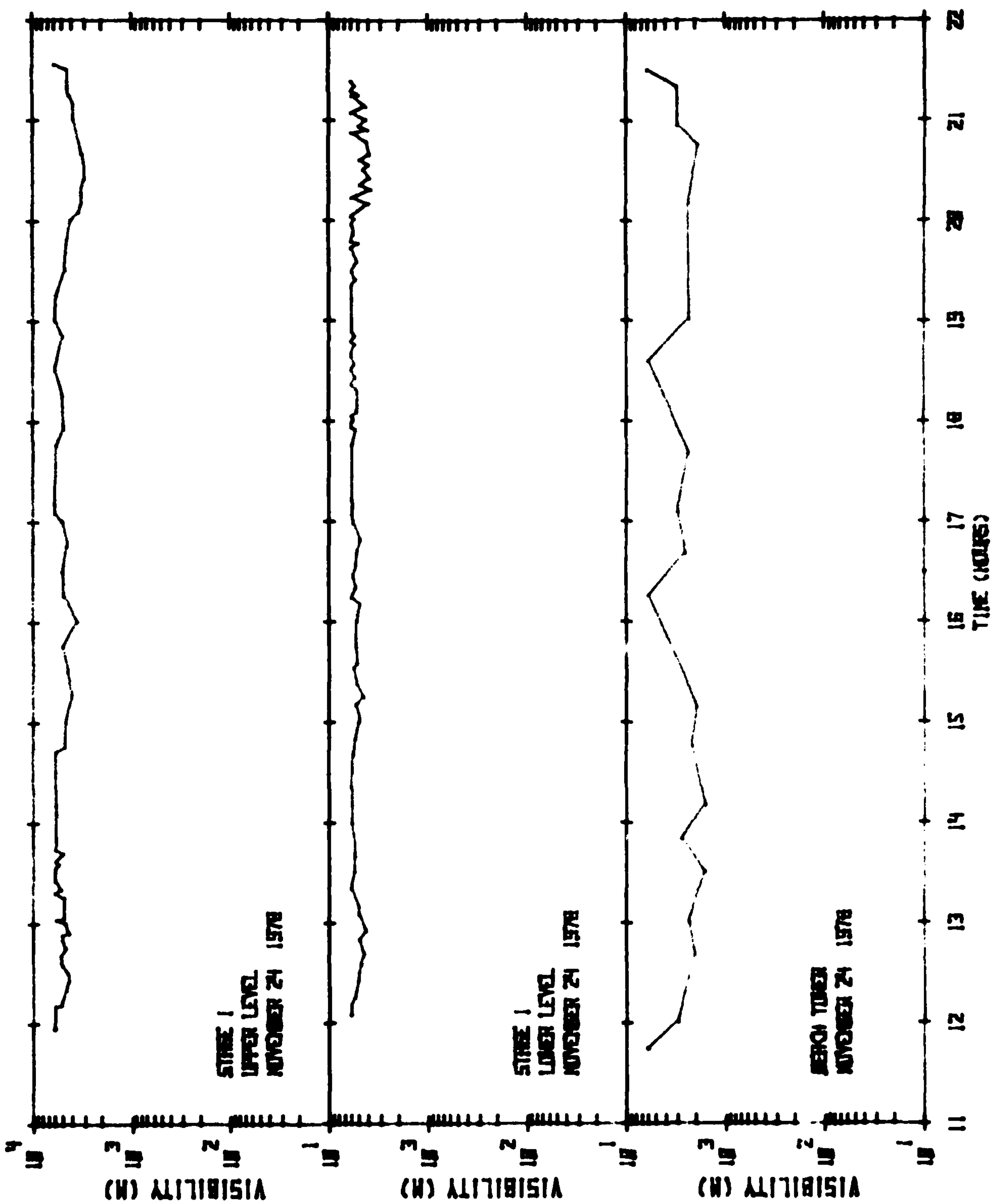

VISIBILITY (M)
TIME (HOURS)
BEACH TOWER
NOVEMBER 11 1978
10^1
10^2
10^3
10^4
10
11
12
13
14
15
16
17
18
19
20


BEACH TOWER
NOVEMBER 14 1978
TIME (HOURS)
VISIBILITY (M)
1
2
3
4
5
6
7
8
9
10
11
10^1
10^2
10^3
10^4

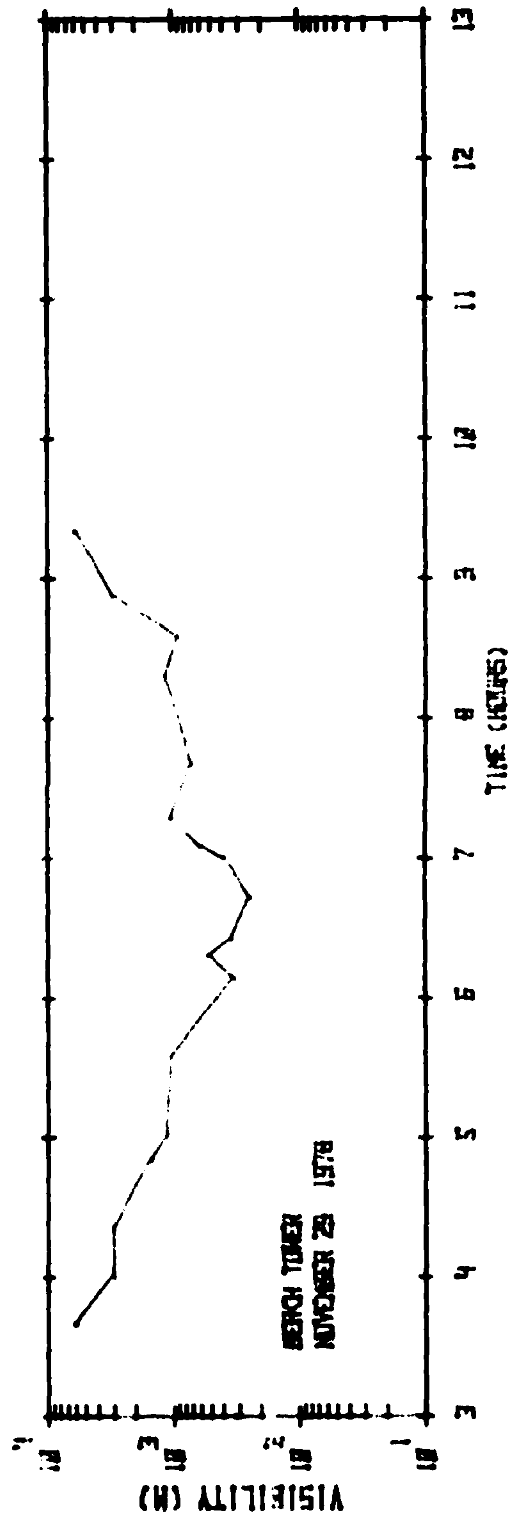

VISIBILITY (M)
TIME (HOURS)

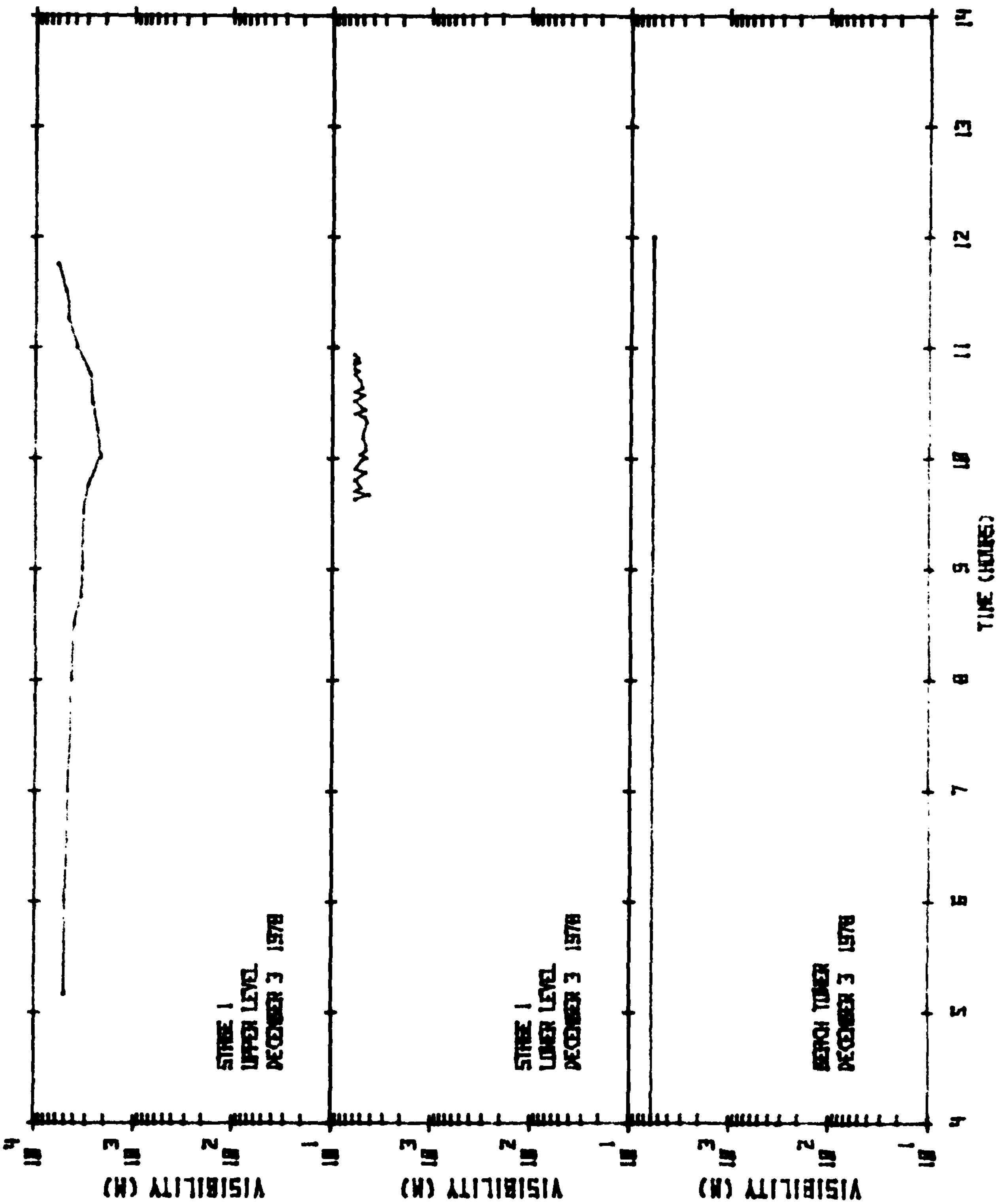

STAGE 1
UPPER LEVEL
NOVEMBER 28 1978
STAGE 1
LOWER LEVEL
NOVEMBER 28 1978
BEACH TOWER
NOVEMBER 28 1978
VISIBILITY (M)
VISIBILITY (M)
VISIBILITY (M)
TIME (HOURS)
5
6
7
8
9
10
11
12
13
14
15


BEACH TOWER
NOVEMBER 21 1978
VISIBILITY (M)
TIME (HOURS)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
10^1
10^2
10^3
10^4



STAGE 1
UPPER LEVEL
NOVEMBER 24 1978
STAGE 1
LOWER LEVEL
NOVEMBER 24 1978
BEACH TOWER
NOVEMBER 24 1978
VISIBILITY (M)
VISIBILITY (M)
VISIBILITY (M)
TIME (HOURS)
11
12
13
14
15
16
17
18
19
20
21
22


BEACH TOWER
TIME (HOURS)
VISIBILITY (M)


STAGE 1
UPPER LEVEL
DECEMBER 3 1978
STAGE 1
LOWER LEVEL
DECEMBER 3 1978
BEACH TOWER
DECEMBER 3 1978
VISIBILITY (M)
VISIBILITY (M)
VISIBILITY (M)
TIME (HOURS)
4
5
6
7
8
9
10
11
12
13
14

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